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METEORITICS

NO. 19

by Ye. S. Burkser, et al.

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No. 19

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I. THE AGE OF METEORITES

by Ye. S. Burkser

Russian Text Pages 3-11.

(Paper given before the expanded plenary meeting of the Committee on Meteorites, Academy of Sciences, Ukrainian SSR, 7 May 1959.)

The material in meteorites has not undergone such complex changes in composition and structure as have terrestrial rocks through the geological history of the earth. Therefore, the determination of the absolute age of meteorites is of great importance in solving the problem of the age of our planetary system.

The presence of radioactive elements in stone and iron meteorites opens a path for establishing the absolute age of the material of which they are made. At the same time it is necessary to remember that the amount of radioactive elements in the material of meteorites is extremely small, so that accurate determination of their content presents a very complicated problem for the investigator.

The first determinations of the absolute age of iron meteorites were made by F. A. Paneth in 1928-1931 (Ref. 1). Paneth started with the experimentally proven fact that when heated to temperatures below 1000°, iron-nickel meteorites retain their helium content, formed from the decay of uranium and thorium atoms. By dissolving the metal in mineral acids one can separate the helium contained in the material and establish the quantity contained, as well as the uranium content of the meteorite. Paneth gave figures on the age of 22 iron meteorites in an article published in 1930. Their age was found to be within a range of 100-2900 millions of years (Ref. 1).

It is essential to note that the methods which Paneth used for determining uranium by radon were not sufficiently perfected. In subsequent work Paneth considerably improved his methods for determining the quantity of radon and thoron in meteorites, by which he established the uranium and thorium content. The amount of radioactive gases was established by photoregistration of the alpha particles emitted by them. As a result of these measurements, Paneth established a significant discrepancy between the new and the old figures on the age of iron meteorites. An article published in 1942 gave a value of 6900 million years instead of 2900 million years for the Mount Ayliff meteorite.

In 1942 Arrol, Jacobi, and Paneth (Ref. 2) generalized the work which had been done previously by Paneth and his co-workers on

determining the helium content in iron meteorites. No important dis-
crepancies in the helium content, as compared with the data of previous
investigations, were found, but the uranium content in iron meteorites

was reduced on the average to $0.7 \cdot 10^{-8}$ g/g and the thorium content was

accepted at $4 \cdot 10^{-8}$ g/g. As shown by the latest investigations, however,
these values are also exaggerated.

The high values for the ages of a number of meteorites (counting
from the time of solidification) calculated by Paneth on the basis of
their helium content and the average content of uranium and thorium pro-
vided a basis for assuming that the age of our planetary system might be
determined in this way. At the same time, however, Paneth noted that
samples of certain meteorites of different size but belonging to the
same fall contained different amounts of helium with almost identical
uranium and thorium content. The fact that the meteorites were in inter-
planetary space excludes all possibility of migration of radioactive
elements except leakage of gases; but laboratory investigations of the

behavior of iron meteorites at temperatures up to 1000° have shown a
small loss of helium. Consequently, any significant losses of helium
could take place only when meteorites passed at minimal distances from
the sun.

Paneth considered that, taking all the radioactive elements in
them into account, the error in his determinations of the ages of meteor-
ites did not exceed ± 1000 million years for the oldest meteorites or 20
percent for the least ancient ones.

It would seem that in view of the conditions of interplanetary
space, one would expect loss of helium particles to be most likely. The
most recent works devoted to the study of cosmic rays, which act contin-
uously on meteorites not protected from them by the earth's envelope,
show the possibility of the production of helium by the destruction
of the nuclei of chemical elements by cosmic rays. A. P. Zhdanov (Ref.
3) has proved the existence of nuclear fragmentation by cosmic rays.

They are quite rare at sea level --1 cm^2 of thick photographic film in-
dicates 5 - 6 fragmentations per month; but this number is increased 50
times at an altitude of 7000 meters. The photographic films show the
characteristic "stars" which give evidence of nuclear disintegration.

A number of investigators have demonstrated the production of
alpha particles when nuclei are split by cosmic rays. Cosmic rays act-
ing on the glass covers of photographic emulsions cause the formation of

"stars" whose rays are caused by alpha particles. A quantity of 10^5

helium atoms can be produced in 1 cm^3 of glass in a year under the influence of cosmic rays. The same process could also take place in stone meteorites.

In 1947 Bauer published an article devoted to the possible production of helium in meteorites under the influence of cosmic rays. If we compare the logarithms of the masses of meteorites in kilograms and their helium content in a diagram, then an inverse relationship appears with a considerable degree of approximation. If a meteorite was broken into separate parts in its fall, Bauer took the mass of all its particles to be the mass of the meteorite. Bauer cast doubt on Paneth's figures on the age of meteorites by his calculations of the rate of production of helium in meteorites under the action of cosmic rays.

The discovery of an isotope of helium with an atomic weight of 3 led to the establishment of the presence of a significant He^3 content in iron meteorites when the gases liberated by the meteorites were investigated. Paneth, Reasbeck, and Mayne in 1952 - 1953 (Ref. 5) and Paneth in 1953 (Ref. 6) reported the results of determinations of helium in five iron meteorites with very different content of helium isotope with atomic number 3. The results of their determinations are given in Table 1.

Meteorite	Helium Content 10^{-6} cm^3/g	$\dfrac{He^3}{He^4}$, %
Mount Ayliff	36.8	31.5
Carbo	22.0	28.6
Toluca	18.9	29.7
Bethany Amalia	3.4	27.8
Bethany	0.36	17.8

Table 1.

The formation of He^3 in meteorites is proof that this isotope, and, probably, part of the He^4 isotope is not of radiogenic origin, but that both isotopes are products of the destruction of chemical elements contained in the meteorite by cosmic rays. If we take the rate of formation of He^3 to be $5 \cdot 10^{-14}$ cm^3/g per year, on the basis of Singer's

works (Ref. 7), then the accumulation of the quantity of He^3 found in the Toluca, Carbo, and Mount Ayliff meteorites would have required from 10^8 to 10^9 years on the assumption that the intensity of the cosmic rays had remained constant during this time.

In an article which he published in 1953 (Ref. 8), Paneth admitted serious errors in his previous determinations of the uranium and thorium in iron meteorites and presented new figures: The uranium content was $0.007 \cdot 10^{-6}$ g/g, thorium $0.004 \cdot 10^{-6}$ g/g. Thus, the problem of the age of iron meteorites remained unresolved.

Patterson (Ref. 9) took up the study of the isotopic composition of the lead contained in stone and iron meteorites. The isotopic composition of lead separated from continental rock at different ages in the history of the earth is distinguished by different contents of the isotopes Pb^{204}, Pb^{206}, Pb^{207}, and Pb^{208}. The isotopes Pb^{206}, Pb^{207}, and Pb^{208} accumulate continuously with time with a constant content of the non-radiogenic isotope Pb^{204}; but any quantities of these isotopes could be present in primary non-radiogenic lead. The following ratios have been used in making a comparison of the age variations in the isotopic composition of lead:

$$\frac{Pb^{206}}{Pb^{204}}; \quad \frac{Pb^{207}}{Pb^{204}}; \quad \frac{Pb^{208}}{Pb^{204}}.$$

The illustration shows the distribution of lead isotopes with respect to the Pb^{204} isotope, whose content is taken to be unity. (See Collected articles Yadernaya geologiya (Nuclear Geology), IL (Publishing House for Foreign Literature), 1956, page 389.). The experimental sites quoted were chosen on the basis of determinations of the isotopic composition of lead separated from lead ores and rock of known geological age. Determinations which indicated anomalous isotopic composition of lead are not included. Such samples yield a low age which does not correspond to the geological conditions of formation. Extrapolation of the derived curves leads to a time of zero Pb^{206} content of about 5 billion years. The lowest values of the ratios

$$\frac{Pb^{206}}{Pb^{204}}; \quad \frac{Pb^{207}}{Pb^{204}}; \quad \frac{Pb^{208}}{Pb^{204}}$$

are characteristic for lead from the Canyon Diablo and Henbury iron

meteorites.

.The very low uranium and thorium content in iron meteorites does not make any noticeable change possible in the time of the derived relationships in iron meteorites. Therefore, the isotopic composition of the lead contained in them can be considered primary without any great error. The age of a meteorite can be calculated, in accordance with the data from an isotopic analysis of the lead separated from it, by the following formula:

$$\frac{R_{1a} - R_{1b}}{R_{2a} - R_{2b}} = \frac{e^{\lambda_1 T} - 1}{K(e^{\lambda_2 T} - 1)}.$$

Making use of the quoted formula in which

$$R_1 = \frac{Pb^{207}}{Pb^{204}}; \quad R_2 = \frac{Pb^{206}}{Pb^{204}},$$

a and b denote different meteorites, λ_1 and λ_2 are constants of the radioactive decay of U^{235} and U^{238} while $K = \frac{U^{238}}{U^{235}} = 137.8$. Patterson calculated the ages of three stone meteorites, taking the lead from the Henbury and Canyon Diablo meteorites to be primary. On the basis of the data presented in Table 2, Patterson determined the average age of the stone meteorites to be $4.55 \pm 0.07 \cdot 10^9$ years.

Meteorite	Isotopic Composition $Pb^{204} = 1$				Age, 10^6 years
	$\dfrac{Pb^{206}}{Pb^{204}}$	$\dfrac{Pb^{207}}{Pb^{204}}$	$\dfrac{Pb^{208}}{Pb^{204}}$	$\dfrac{Pb^{207}}{Pb^{206}}$	
Nuevo Laredo	50.28	34.86	67.97	0.60	4600
Forest City	19.27	15.95	39.05	0.57	4500
Modoc	19.48	15.76	38.21	0.54	4400
Henbury	9.55	10.38	29.54		
Canyon Diablo	9.46	10.34	29.44		

Table 2.

An attempt to apply the lead method for determining the age of
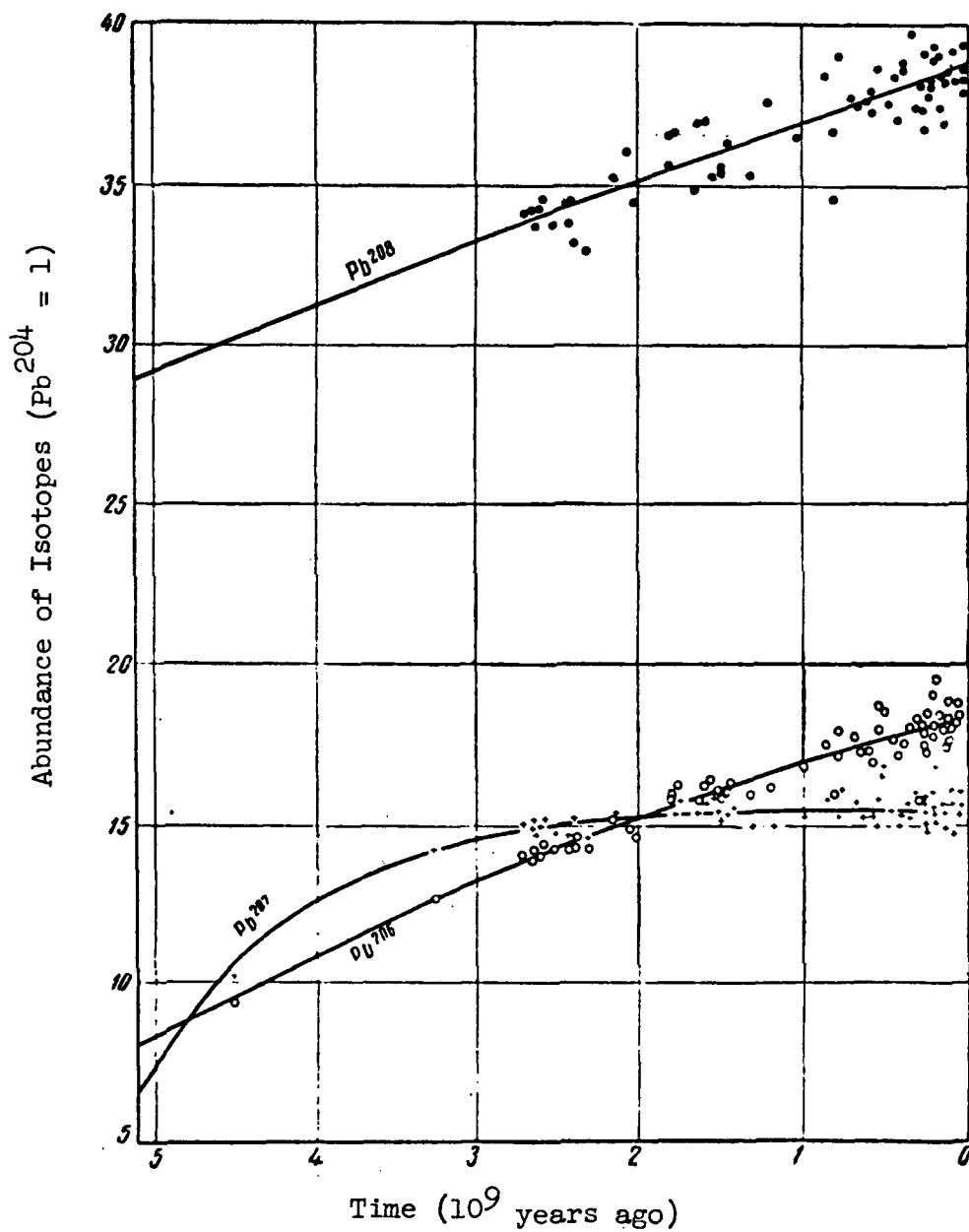
The Abundance of Isotopes of Lead (Taking $Pb^{204} = 1$),
Given as a Function of Time.

meteorites was made in a work by M. M. Shats (Ref. 10). M. M. Shats determined the uranium and lead content in several stone meteorites. The age of these meteorites was calculated by the lead-lead method and does not depend on data on chemical determination of uranium. The results of these determinations are presented in Table 3; they give the uranium

content in stone meteorites as being on the order of 10^{-7} g/g.

Meteorite	Uranium Content, 10^{-7} g/g	Pb/Pb Age, 10^9 years
Saratov	4.0+0.5	4.5
Kunashak	5.3+0.8	4.4
Yelenovka	4.8+0.5	4.5
Norton County	5.7+0.5	3.9

Table 3.

Ebert, Koenig, and Waehnke (Ref. 11) used a method of neutron irradiation to split uranium atoms with subsequent determination of the product of splitting--xenon, with an atomic weight of 133, in order to determine the uranium in stone meteorites. This isotope accumulates in the amount of 6.5 percent in fission products of uranium 235 nuclei. This method permits determination of small quantities (on the order of

10^{-9} g) of uranium. The authors studied three chondrites --the Pultusk, Breitscheid, and Akaba stones.

These same meteorites, except the Pultusk stone, were studied by Herneyger and Waenke (Ref. 12), who also irradiated the meteorites with neutron fluxes for 14 days. They made use of the barium isotope with an atomic weight of 140 of the products obtained from splitting uranium nuclei. The results they obtained in respect to the uranium content in

the meteorites (in units of 10^{-8} g/g) are presented in Table 4.

The helium content of the Akaba, Beddgelert, and Breitscheid meteorites was determined, and their ages were calculated on the assumption that the thorium content was three times as great as the uranium content.

The ages of these meteorites lay within a range of 3.6 to 3.8·10^9 years, but the assumption that the helium is of radiogenic origin is

wholly unfounded. An additional assumption was made that the ratio $\frac{Th}{U}$ = 3, which has not been confirmed by other investigators

Meteorite	Methods		
	Xenon	Barium	Luminescence
Pultusk	1.2		
Akaba	0.8	0.9	0.8
Beddgelert	2.8		
Breitscheid	1.2	1.5	

Table 4.

The thorium content in stone meteorites (chondrites) was determined by Bate, Huinzeng, and Potratz (Ref. 13) in 1957 by a neutron activation method with an accuracy of up to ± 10 percent. The data from these determinations are presented in Table 5.

Meteorites	Thorium, 10^{-8} g/g	Uranium, 10^{-8} g/g
Forest City	4.7	1.0
Beardsley	4.3	1.0
Holbrook	9.0	1.3
Modoc	4.5	1.1
Nuevo Laredo	54.0	13.0

Table 5.

Several investigators have applied the argon method for determining the absolute age of stone meteorites. Data on determinations of age by the argon method are given in Table 6.

The ages of the meteorites found by Gerling and Pavlova in 1951 were underestimated as the result of overestimation of their potassium content.

With a ratio of $\frac{\lambda_K}{\lambda_\beta}$ = 0.125, the data from the argon method establish the ages of stone meteorites within a range of 0.64 to $4.5 \cdot 10^9$ years. If we make use of the following constants accepted by the Commission on the Determination of the Absolute Age of Geological

Formations in 1959 for the process of radioactive transmutation of potassium: the content of the isotope K^{40} = 0.0122 percent, λ_K = 5.57·

·10^{-11}, λ_β = 4.72·10^{-10}, then recalculate the ages of the Krymka, Yelenovka, and Zvonkovoye meteorites, we obtain the results given in Table 7.

The data presented here imply that the maximum age of stone meteorites, as determined by the argon method, is 4.5 billion years; but the age is considerably less in some cases. Changes in the thermodynamic conditions which caused recrystallization of the meteoritic substance may be the cause of this phenomenon. The age of the Migeya meteorite, which contains volatile organic compounds (a feature which proves the absence of overheating during its life), is 4.3 billion years.

Table 6.

Meteorite	Age, 10^9 Years	Type of Meteorite	Data of Published Source, Investigator
Kashin	3.00	Chondrite	1951 (Ref. 14), E.K. Gerling and K.G. Pavlova
Zhovtnevyy Khutor	3.00	"	" "
Pervomayskiy Poselok, black variety	1.8	"	1956 (Ref. 15), E.K. Gerling and L.K. Levskiy
Pervomayskiy Poselok, gray variety	0.64	"	" "
Padvarninkyay	1.00	Achondrite	" "
Kunashak, gray variety	0.70	Chondrite	" "
Staroye Pes'yanoye	4.2	Achondrite	" "
Okhansk	4.5	Chondrite	" "
Yelenovka	4.0	"	" "
Saratov	3.8	"	" "
Bjurboele	3.6	"	" "
Yelenovka	4.19	"	1958 (Ref.16), Ye. S. Burkser, B.B. Zaykos, F.I. Kotlovskaya
Krymka	3.84	"	" "
Zvonkovoye	4.04	"	" "
Beardsley	4.28		1955 (Ref. 17), Wasserburg and Heyden

Table 6. (Continued)

Meteorite	Age, 10^9 Years	Type of Meteorite	Data of Published Source, Investigator
Holbrook	4.20		1955 (Ref. 17), Wasserburg and Heyden
Forest City	4.12		1955 (Ref. 18), Reynolds and Lipson
Brenham	3.0		1955 (Ref. 19), Thompson and Mayne
Akaba	3.8		" "
Monze	2.0		" "

Schumacher (Ref. 20) applied the rubidium-strontium method for determining the age of stone meteorites. The Forest City chondrite was studied. It was found that the Sr^{87} content was 10 percent higher than is normally found for strontium of non-radiogenic origin. If we accept that age of the meteorite to be equal to $4.5 \cdot 10^9$, then we obtain good agreement with the new constant for rubidium; its corresponding half-life is $5 \cdot 10^{10}$ years.

Meteorite	Age, 10^9 Years
Krymka	4.07
Yelenovka	4.40
Zvonkovoye	4.27

Table 7.

On the basis of data obtained from applying the lead/lead, argon, and rubidium-strontium methods, a maximum age of 4.5 billion years has been established for stone meteorites, which considerably exceeds the age of the minerals of the earth's crust which have been studied up to the present time.

The question of the age of iron meteorites is less clear. Their exceedingly low uranium and thorium content, the lack of data on the isotopic composition of primary lead, and also the process of splitting

of nuclei of such meteorites by cosmic rays, hamper·the application of radiometric methods for determining their ages.

Stoenner and Zahringer (Ref. 21) have undertaken to attempt to apply the argon method to determining the absolute age of iron meteorites. An activation method was used for quantitative determination of the argon and potassium contents of iron meteorites. A neutron flux caused by the formation of radioactive isotpes of argon and potassium by the $Ar^{40}(n, \gamma) Ar^{41}$ and $K^{41}(n, \gamma) K^{42}$ reactions. The quantity of radioactive isotopes was determined radiometrically. In addition, the He^3 content was determined.

On the strength of experiments designed to determine the content of potassium and radiogenic argon in the Canyon Diablo and Toluca iron meteorites, the authors calculated the age to be within a range of 5.3 to $13 \cdot 10^9$ years. The negligible argon and potassium contents and the wide dispersion in the data obtained do not permit one to agree with the the age found here on the order of 10 to $13 \cdot 10^9$ years for the Canyon Diablo meteorite. The problem of the age of iron meteorites cannot be considered as solved at present.

It would be desirable to set up experiments to determine the age of iron meteorites by the rubidium-strontium and rhenium-osmium methods if the amounts of these elements in the mass of a meteorite turn out to be accessible for a sufficiently accurate quantitative determination, including establishment of the isotopic composition of strontium and osmium. Due to their insignificant concentration, the ratio of these elements could not be changed under the action of cosmic rays (due to their formation from heavier elements or due to destruction).

The determinations of the ages of stone meteorites by the different methods which have been presented here yield a maximum value of 4.5 billion years, corresponding to the beginning of the process of the accumulation of products of radiogenic decay in them. This process could take place prior to the formation of meteorite bodies with any significant mass. The processes of accumulation of radiogenic lead and strontium could take place in dust-like material.

Argon could be accumulated and retained without loss with particle sizes on the order of 0.05 - 0.1 mm. Losses of argon should have stopped after agglomeration of the dust-like material. A large number of most reliable data on the age of stone meteorites obtained by the argon method lie within the range of 4 to 4.4 billion years. Thus, the argon method gives some idea of the age of accumulation of particles

while the lead and the rubidium-strontium methods give some idea of the age of the substance.

If we consider that the age of uranium nuclei (not exceeding a 2 : 1 ratio of the U^{238} and U^{235} contents at the outset) is 5 billion years, then the formation of accumulations of dust-like materials in our planetary system must have taken place about 4 to 5 billion years ago.

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II. SOME PROBLEMS OF THE CHEMISTRY OF METEORITES

by A. A. Yavnel'

Russian Text Pages 12-25.

(Paper given before the Expanded Plenary Meeting of the Committee on Meteorites of the Academy of Sciences, Ukrainian SSR, 8 May 1959.)

Chemical investigations of meteorites constitute an important branch of meteoritics, which has the objective of solving the problems of the origin and evolution of meteorites. These investigations have provided material for clarification of the following processes which take place in meteoritic material at all stages of its history:

1) the formation and evolution of meteors (meteorite-forming bodies) in interplanetary space;

2) the movements of meteors (meteoric bodies) in the terrestrial atmosphere;

3) collisions of meteors with the surface of the earth; and

4) changes in meteoritic material under terrestrial conditions.

In this article we shall present a general outline of the basic data on the chemistry of meteorites which are of importance to meteoritics without touching upon their applications to cosmogeny, geochemistry, physics, and other sciences.

I

The majority of the chemical studies of meteoritic material have been directed toward the solution of the basic problem of meteoritics-- the problem of the origin of meteorites. These investigations are associated most closely with the determination of the following characteristics of meteoritic material.

The Average Chemical Composition of Meteoritic Material

The determination of the average chemical composition of meteoritic material is important for clarification of certain general processes which take place in the early stages of their formation.

Calculating the average composition of meteoritic material is made difficult by the following factors:

a) the possibility of lack of correspondence between the composition of meteorites which have reached the surface of the earth and the composition of meteoric material in interplanetary space due to selection of meteoritic material during its passage through the earth's atmosphere; and

b) the well-known indeterminateness of the quantity of the components of meteoritic material--the silicate and metallic phases, and the accessory minerals, of which the most abundant is troilite.

At present we can only assume the existence of exceedingly friable meteor bodies, possibly of special composition, which are completely destroyed in the earth's atmosphere. As Baker has recently demonstrated theoretically (Ref. 1), only an insignificant portion of such bodies, by reason of particularly favorable conditions of motion (glancing trajectory, certain relationships between the magnitude of geocentric velocity and the minimum distance of initial trajectory from the earth) can ever become earth satellites within a given period and then, after gradual deceleration in the atmosphere, fall on its surface.

However, we do not have any data at all on the composition and the numbers of these hypothetical bodies; therefore, in determining the average composition of meteoritic material, we usually start with the average composition of meteorites which have fallen on the earth's surface which is apparently an admissible approximation.

Determination of the relative number of phases in meteoritic material presents greater difficulty. Investigators have essentially taken three courses for the solution of this problem. Some scientists (Noddack (Ref. 2) and Brown (Ref. 3))have obtained these data from the ratio of the masses of the earth's core and mantle, assuming that the total composition of the earth is the average composition of meteoritic material. According to their calculations, the weight of the metallic phase of meteoritic material accounts for about 2/3 of the weight of the silicate phase.

Another way has been to determine the relationship of phases by the relative weight of meteorites of different classes: stone, iron-stone, and iron. It is obvious that only data on meteorites collected after observed falls are suitable for this purpose. Such investigations have been made by Borgstrom (Ref. 4), P. N. Chirvinskiy (Refs. 5, 6), then by B. Yu. Levin, S. V. Kozlovskaya, and A. G. Starkova (Ref. 7). The authors of the work (Ref. 7) made the most painstaking approach to the problem of the statistics of meteorites and restricted the upper limit of the mass of the meteorites they examined to a value of 150 kg, on the basis of general considerations.

We obtained similar results by studying the distribution of all iron meteorites on the basis of their composition (nickel content). All iron meteorites were divided for this purpose into six weight classes: up to 1, 10, 100, 1,000, 10,000, and 100,000 kg respectively. Then the weight distribution of meteorites by composition was found for each weight class. In view of the fact that deviations of the obtained values from the true distribution are of a random nature, their average

value should be the most accurate. On the other hand, it is obvious that the greatest deviation should be observed for the first classes (on account of the small number of meteorites) and for the last (in view of the influence of single large meteorites on the result), while optimal conditions should prevail for the average classes in which the results should be closest to the true result, that is, to the average in our case. When the average distribution we obtained was compared with the distribution of meteorites of each class, it was found that it practically coincided with the data for meteorites with weight up to 100 kg; that is, it was necessary to restrict ourselves to meteorites up to this weight for statistical purposes.

Thus, our data confirm quite well the value for the upper limit of the mass of examined meteorites obtained by B. Yu. Levin and others: this implies the correctness of their results with respect to the relationship between the total masses of meteorites of different classes (close to the data of Borgstrom (Ref. 4) and P. N. Chirvinskiy (Ref. 5)). Our recalculation of these results indicated that the metallic phase of meteoritic material accounts for 32 percent of the silicate phase: that is, about half the amount obtained previously by Noddack and Brown.

It is essential to bear in mind that this result reflects the relationship of masses of meteorites collected on the site of their fall, not that of meteorites in interplanetary space. When moving through the earth's atmosphere, the less durable stone meteorites apparently should be subjected to greater destruction than iron ones. Moreover, it is less likely that stone meteorites will be collected on the site of their fall than iron meteorites, because they are not so noticeable on the earth's surface. All this compels one to draw the conclusion that the ratio of the metallic and the silicate phases obtained on the basis of data on meteorite falls represents an upper limit. This also implies that the large figures obtained by Noddack and Brown are exaggerated.

In a later article Noddack (Ref. 8), then Urey (Ref. 9), suggested taking the average composition of chondrites, the most abundant type of stone meteorite, as the average composition of meteoritic material. According to the latest data obtained by the author and M. I. D'yakonova (Ref. 10), the metallic phase of chondrites amounts to only 15.5 percent of the silicate phase. In the meantime, when calculating the average composition of meteorites, it is necessary, of course, to take the presence of iron and iron-stone meteorites into account, which should increase the relative amount of the metallic phase. Thus, the ratio of phases obtained on the basis of the composition of chondrites can be regarded as a lower limit. This implies that the true proportion of the metallic phase in the silicate phase should be between 32 and 15.5 percent.

Some investigators believe that this ratio should be closer to

the chondrites. For example, A. Ye. Fersman (Ref. 11) and Goldschmidt (Ref. 12) believed that this value is equal to 20 percent; according to the data of B. Yu. Levin and others (Ref. 7), it should be 17.5 percent.

Data on the relationship of the phases (also troilite) are presented in the Table for clarity.

Phase	Chondrites (Ref. 10)	Falls (Ref. 7)	Average		
			(Ref. 11)	(Ref. 12)	(Ref. 7)
Silicate	100	100	100	100	100
Metal	15.5	32	20	20	17.5
Troilite	7.7	7	4	10	7.8

It is possible to make use of the extreme limits of the table to evaluate the error permitted in the calculation of the average composition. It turns out that for the majority of elements the difference between the upper and the lower limits has very little effect on the result. The greatest divergence can be seen in elements not included in the silicate phase: Ni, Co, Cu, Ag, Au, and the platinum metals. In this case, however, the ratio of the extreme figures does not exceed 1.7 and if we bear in mind that we are accepting an intermediate value, then the possible error is not large in this case.

Thus, in spite of the well-known indeterminateness of the ratio of phases in meteoritic material, one can speak quite confidently of its average composition. The work done in recent years on the determination of many elements in meteorites has permitted improvement of the original data for calculating the average composition of meteoritic material. Such calculations were made recently by B. Yu. Levin, S. V. Kozlovskaya, and A. G. Starkova (Ref. 7).

Considering the matter from the standpoint of the formation of meteoritic material, it is interesting to compare its average composition with the composition of the sun, even though only the solar atmosphere is accessible to us for study. This comparison was made recently by V. V. Cherdyntsev (Ref. 13) who showed that the volatile elements have been lost in meteorites--hydrogen, carbon, nitrogen, and the inert gases. The content of the latter is 5 to 6 orders lower than the basic curve of abundance of the elements as a function of the atomic weight. This difference is explained, apparently, by the losses of such elements during the formation of these bodies. At the same time, it must be noted that the inert gases in meteorites are essentially of secondary origin as the result of radioactive processes and nuclear reactions under the action of cosmic rays. Only in rare cases do we observe an

anomalously high content of He, Ne, and A; for example, in the Staroye Pes'yanoye white calcium enstatite achondrite (borite); E. K. Gerling and L. K. Levskiy (Ref. 14), studied this meteorite, explain a considerable portion of these elements on the basis of primary derivation.

One's attention is attracted toward the general increase in the relative abundance of heavy elements in meteoritic material as compared with the sun's atmosphere. In particular, the relative abundance of the elements of the V and VI periods of the periodic table is 1 - 1.5 orders higher than the abundance of elements of the III and IV periods. At the same time, the relative enrichment with the heavy elements does not depend on their chemical properties.

In view of the fact that the abundance of elements in meteorites is closer to the theoretical curve of abundance for isotopes than is that of the solar atmosphere, one may well consider it possible that meteoric content in respect to the light elements likewise more closely approximates the original content than does the solar atmosphere. V. V. Cherdyntsev (Ref. 13) concludes from this that the solar atmosphere was more likely enriched with light elements as the result of gravitational differentiation of the material in the sun. Thus, the difference in the composition of meteorites and the solar atmosphere is apparently explained by this reasoning, not by losses of light elements in the meteoritic material.

Such are the significant conclusions which may at the present time be arrived at from an examination of the average composition of meteoric material.

Patterns in the Chemical Composition of Meteoritic Material

Generalization of many years of investigation of the chemical composition of meteorites of different classes and subclasses make it possible to note some general patterns in the composition of meteoritic material which are important in genetic respects. At the same time, in spite of a general similarity in meteorites of a given subclass, one can discover certain differences among them.

Thus, as early as 1916, Prior (Ref. 15) established a connection in chondrites between the ratio of the silicate and metallic phases and their composition--the FeO content in the silicate and the Ni in the metal.

Urey and Craig (Ref. 16) discovered lately that chondrites can be divided by their total iron content into two clear-cut groups (not counting carbonaceous ones). On the basis of this fact they suggested that the meteorites were formed out of two asteroids of different composition.

Applying the Prior criterion, the present author (Ref. 17, 18) found five groups of chondrites by examining the ratio and the composition of phases, the carbonaceous chondrites occupying a place in the fifth group (with a decrease in the amount of the metallic phase).

The latest investigations of the chemical composition of chondrites have essentially confirmed the existence of these groups. Wiik (Ref. 19) showed the existence of the first, second, and third groups of chondrites by the total iron content in the nonvolatile part. He classed carbonaceous chondrites by this criterion in the first group with enstatite chondrites, and he did not investigate chondrites of the fourth group (amphoteric).

Brown and MacKinney (Ref. 20) established the presence of the first, second, third, and fourth groups of chondrites by the ratio of Fe, Ni, and Co to Mn and Cr. These authors did not study carbonaceous chondrites.

M. I. D'yakonova and V. Ya. Kharitonova (Ref. 21) found chondrites of the second, third, and fourth groups by the ratio and the composition of phases. They did not analyze enstatite and carbonaceous chondrites.

In our opinion, the most clear-cut separation of chondrites into groups can be made by the relationship between combined iron (in the form of FeO and FeS) and metallic iron.

We have noted the presence of several groups of iron meteorites in the above-mentioned works (Refs. 17, 18) which differ from each other by their nickel content. In addition, separation into groups and other subgroups of meteorites is intended--pallasites, achondrites, etc. This situation lends strength to the assumption that meteorites were not formed from one, but from several original bodies.

Brown and his co-workers (Refs. 22, 23) have found a pattern in their discovery of gallium and germanium in iron meteorites as small admixtures. Iron meteorites are divided into four groups by their content of these elements, and these groups differ structurally to a certain extent (width of the kamacite bands).

Our studies of this problem, with use of experimental data from Brown and others, permitted establishing a different dependence of the structure of meteorites of different Ga - Ge groups on their nickel content. It was found that when passing from a group with a smaller gallium and germanium content to a group with a larger content, the dependence of the width of the kamacite bands on the nickel content showed a regular increase. One may assume from this that the presence of Ga - Ge groups in iron meteorites indicates different conditions of formation.

Thus, the available material from study of the patterns in the composition of meteorites of different classes provides evidence of irregular distribution of elements in meteoritic material, which may be explained by the formation of the meteorites under different conditions and from several parent bodies.

The Chemical Composition of Phases of Different Classes of Meteorites

A comparative study of the composition of corresponding phases of different classes of meteorites makes it possible, when these classes are separated, to find general patterns in them which are important in establishing the genetic ties between them. The most favorable object of study in this respect is the metallic phase, which is contained in meteorites of all three classes--iron, iron-stone, and stone.

Brown and Patterson (Ref. 24) established the difference in the average nickel content in the metallic phase of stone meteorites and in iron meteorites. In addition, they assumed that the composition of the metallic phase in stone meteorites gradually approaches the average composition of iron meteorites.

The discovery of groups among the stone and iron meteorites mentioned previously led us to the idea of comparing the nickel content in these groups of meteorites of different classes. As a result of these investigations (Ref. 18), it was found that there is a definite similarity in the nickel content in certain groups of iron, stone, and also iron-stone meteorites, and this served as a basis for the assumption regarding a common origin of groups of meteorites of different classes with a similar nickel content in the metallic phase. Separation of meteorites into classes (subclasses) and general groups served as a basis for the classification of meteorites by their composition that we have suggested.

By comparing the data they obtained on gallium and germanium content, Brown and others (Ref. 23) found the similarity (indicated thereby) between the metallic phase of iron-stone meteorites and one of the Ga - Ge groups of iron meteorites.

Important data on the interrelationship of phases in meteorites can be obtained by their isotopic analysis. Precise investigations of the isotopic composition of some light elements made by A. P. Vinogradov and his co-workers (Refs. 25, 26, 27) showed the absence of isotope shifts in sulfur, carbon, and oxygen in different classes of meteorites.

The exceptional constancy in the isotope ratios of sulfur (S^{32}/S^{34} = 22.20) and carbon (C^{12}/C^{13} = 90.6) in stone and iron meteorites, and

oxygen $(O^{16}/O^{18} = 490.4)$ in stone and iron stone meteorites provides clear evidence of the common origin of meteorites of all classes. Moreover, in the opinion of A. P. Vinogradov (Ref. 27), the constancy of the isotopic composition of the light elements indicates the absence of different classes of processes of melting, segregation, hydrothermal processes, and other similar processes of fractional differentiation of substances like those which took place in the earth's crust. He assumes that this most probably indicates a process of accumulation of cooled drops of a silicate substance with iron at relatively high temperatures in which there was a uniform distribution of the isotopes of light elements in the silicates and iron.

The Distribution of Elements Among the Phases of Meteoritic Material

Data on the distribution of individual elements among the phases of meteoritic material can make possible an explanation of the presence of equilibrium between the metallic and the silicate phases in meteorites and a determination of the equilibrium temperatures and pressures. Some investigators make use of the ratio of the quantities of iron and nickel in the metallic and silicate phases, also in troilite, for this purpose, which permits calculation of the equilibrium constant for nickel.

The work of Brown and Patterson (Ref. 24) contains calculations of the conditions for equilibrium of phases in stone meteorites. One of the basic shortcomings in these works is the use of excessively high nickel contents in the silicate phase in these calculations due to its contamination by the metallic phase.

Our spectral studies of most carefully selected silicate minerals from some stone and iron-stone meteorites show that the nickel content in the silicate phase does not exceed several thousandths of a percent; this is one or two orders lower than the values used by the above-mentioned authors. In view of the fact that the nickel content in the silicate phase depends materially on the carefulness of its selection, one can assume that the true nickel content (in the form of NiO) is still less, This situation does not permit one to draw any quantitative conclusions at present from the available data.

Calculations of the equilibrium constant for nickel obtained by data on the distribution of nickel between nickeliferous iron and troilite in iron meteorites (Refs. 24, 28) also do not reflect the true picture. According to our data (Ref. 29), nickel can be distributed irregularly in different troilite inclusions and even in one inclusion: this provides the strongest evidence of a non-equilibrium state of the Fe - Ni - S system. Therefore, it is impossible to search for equilibrium conditions on the basis of data on the composition of individual

troilite inclusions and their average composition.

Apparently, attempts to investigate the conditions of equilibrium of phases in meteoritic material have not yet yielded positive results, least of all in respect to the existence of equilibrium.

The Distribution of Elements Among Individual Minerals in Meteorites

A study of the composition of minerals makes possible an explanation of equilibrium as applied to individual minerals which have crystallized in a given phase. It is necessary to determine the ratio of the concentrations of the determined elements in different minerals in the silicate and metallic phases for this purpose.

P. N. Chirvinskiy (Ref. 30) determined the average molecular ratio of FeO : MgO : SiO_2 in olivine (4 : 10 : 7) and pyroxene (2 : 5 : 7) in chondrites. The average content of nickel, cobalt, chrome, copper, gallium, and germanium in kamacite and taenite in several iron meteorites was determined by Nichiporuk (Ref. 31).

However, it is not always possible to make use of average concentrations of elements in minerals for determination of equilibrium. Thus, when studying the basic minerals of the metallic phase - kamacite and taenite - it is necessary to determine the nickel concentration on the very boundary between these minerals in view of their irregular nickel content.

The author, I. B. Borovskiy, and others (Ref. 32) used a method of local x-ray spectral analysis for this purpose, which permitted, despite the irregular composition of kamacite and taenite, determination of equilibrium concentrations of nickel and cobalt on the boundary of these phases in an iron meteorite, a comparison between them and a diagram of the state of the Fe - Ni system, as well as drawing conclusions on the absence of an equilibrium state within the phases.

A similar method was used somewhat later for the same purpose by Maringer, Richard, and Austin (Ref. 33); however, because of inadequate experimental facilities, fewer data were obtained in this work than in the preceding one. Moreover, certain results from measurements were inaccurately interpreted by the authors.

It is necessary to note that this trend in the investigations of the chemical composition of the minerals in meteorites has significant prospects and should receive further development.

Works on the determination of radioactive elements and different isotopes in meteoritic material, which have acquired great development lately, constitute the following large group of investigations. These investigations are directed essentially to obtaining chronological data on meteoritic material and meteorites.

The following trends are associated with these problems.

The Content of Isotopes of Radioactive Elements

A comparison of the ratios of isotopes of radioactive elements in meteorites and in terrestrial rocks permits one to compare the ages of these elements in the meteorites and in the earth.

The most accurate results from measurements of the isotopic composition of uranium and potassium were obtained by Soviet investigators. K. A. Petrzhak, I. N. Semenyushkin, and M. A. Bak (Ref. 34) found that

the ratio of the uranium isotopes U^{235}/U^{238} in stone and iron meteorites was identical (with an accuracy of 3 to 4 percent) to the isotopic composition of uranium of terrestrial origin. A similar result was obtained in the isotopic composition of potassium by G. R. Rik and Yu. A.

Shukolyukov (Ref. 35) who found a correspondence in the $K^{39} : K^{40} : K^{41}$ ratios (with an accuracy of 7 to 9 percent) in stone meteorites and terrestrial rocks.

These data provide evidence of the simultaneous formation of the atomic nuclei of meteorites and the earth, which took place about 5 to 7 billion years ago. This conclusion serves as one of the proofs of the origin of meteorites inside the solar system.

The Content of Radioactive Elements and Isotopes of Radiogenic Elements

Determination of radioactive elements and their decay products makes it possible to find the age of meteoritic material by means of methods which are usually applied for determining the geological age of terrestrial rocks and minerals. When nonvolatile radiogenic elements are formed, the age which is found apparently characterizes the interval of time since the solidification of the meteoritic substance. This includes the results obtained by the Pb/Pb and Rb/Sr methods for determining the age of the material in stone meteorites.

The age of the material in several chondrites, which was determined by the Pb/Pb method by Patterson (Ref. 36), I. Ye. Starik, M. M. Shats, E. V. Sobotovich (Ref. 37), and Marshall, Hess (Ref. 38) varies from 4.4 to 4.7 billion years; the age of the material in achondrites (Refs. 37, 36) is from 3.9 to 4.55 billion years.

Using the Rb/Sr method, Herzog and Pinson (Ref. 39) found that the minimum age of the material in one chondrite was 2.8 to 3.7 billion years, while Schumacher (Ref. 40) and Webster, Morgan, and Smales (Ref. 41), who used the same method, determined the age of the material in another chondrite to be 4.5 to 4.6 billion years. Thus, both methods for determining the age of meteoritic material yield results which are in sufficiently good agreement.

Determination of the age of the materials in stone meteorites by the K/Ar and U/He methods gives somewhat different results. Since argon and helium are quite volatile elements, their content in meteorites could be greater than the determined values as the result of losses from cosmic heating of meteorites.

Thanks to the work of Soviet scientists, the determination of the age of meteoritic material by the K/Ar method has become most widespread.

E. K. Gerling and K. G. Rik (Ref. 42) found that the age of the material in a number of chondrites, as determined by this method, varied within wide limits, from 0.6 to 4.5 billion years. The age of the material in chondrites as determined by Ye. S. Burkser and others (Ref. 43) (3.8 to 4.2 billion years) falls within this range. According to the data of Wasserburg and Heyden (Ref. 44) used for calculating other constants, this value was 4.7 - 4.8 billion years for two chondrites. Finally, Geiss and Hess (Ref. 45) found the age of the material in chondrites within the narrow limits of 4.0 - 1.4 billion years by the K/Ar method, and achondrites in the interval of 0.6 - 4.4 billion years. Reynolds and Lipson (Ref. 46) determined the age of the material in one chondrite to be 3.1 - 3.6 billion years.

In recent times the age of the material of stone meteorites has also been determined by the U/He method. Hernegger and Waehnke (Ref. 47) found that the age of the material in two chondrites was 3.6 - 3.8 billion years while Reed and Turkevich (Ref. 48) discovered two groups of chondrites having ages of 1 and 4 billion years.

Thus, the maximum K/Ar and U/He ages of the material in stone meteorites corresponding to the time of solidification approaches the Pb/Pb and Rb/Sr age.

All these data can provide evidence that the material in stone meteorites went through a stage of separation of phases, apparently about 4.5 billion years ago, shortly thereafter solidified, and finally underwent a period of nearly 4 billion years of quite complicated thermal history.

At present the age of iron meteorites has been determined with

less reliability. The U/He method was applied for this purpose in the earliest works of Paneth and his co-workers (Ref. 49). However, the determination of the age of the material in iron meteorites by this method involves a number of difficulties caused essentially by the following circumstances: a) the accumulation of cosmogenic helium formed as a result of nuclear reactions between iron and cosmic ray particles; b) the difficulty in determining small quantities of uranium in iron meteorites; c) the possibility of leakage of radiogenic helium during cosmic heating of the meteoritic material.

A number of investigations is obviously required to overcome these difficulties.

Thus, in order to take the accumulation of cosmogenic helium into account, it is essential to know the ratio of its isotopes He^3/He_K^4,

which varies with the distance from the original surface of the meteorite. In the case of large meteorites we have suggested a method based on the assumption of the constancy of the ratio of these isotopes in the depths of such meteorites. Preliminary calculations of the value of the

He^3/He_K^4 ratio for the Sikhote-Alin' meteorite carried out with the ex-

perimental data of A. P. Vinogradov, I. K. Zadorozhnyy, and K. P. Florenskiy (Ref. 50) showed that this ratio is actually constant in the deep parts of the meteorite and is equal to ~ 0.24. Knowledge of this value permits one to determine the amount of radiogenic helium in a large

meteorite if the total helium content in it and the He^3/He_K^4 ratio have

been measured. Clarification of the nature of the distribution of isotopes of cosmogenic helium through the depths of an iron meteorite apparently will make it possible to take their content into account in general.

It is also possible to assume that the work on determining the uranium and thorium in iron meteorites, now under study by many investigators, will lead to the solution of this complicated experimental problem, too.

Finally, experiments on heating iron meteorites under different conditions, in particular as suggested by Singer (Ref. 51), will be of help in clarifying the extent of loss of radiogenic helium, thus checking whether cosmic heating can actually influence the results of determination of the age of meteoritic material by this method.

In the meantime, all this compels us to search for ways of

determining the age of the material in iron me᾽ ᴐrites by other pairs of radioactive-radiogenic elements. Recently Geiss and others (Ref. 52) carried out work on determining the osmium in an iron meteorite, which

revealed that a considerable part of the Os^{187} is of radiogenic origin

due to the decay of Re^{187}. Further investigations of the rhenium content should show the possibility of applying a Re/Os method for determining the age of the material in iron meteorites.

Stoenner and Zaehringer (Ref. 53) recently made an attempt to determine the age of the material in iron meteorites by the K/Ar method. However, the results they obtained of 5.3 - 13 billion years clearly do not agree with the age of either the uranium or the material in stone meteorites, with which, as has been shown previously, iron meteorites have a common origin. It is probable that the excessively high results are explained by the complexity of separating radiogenic and cosmogenic elements in iron meteorites.

It should be noted that it was shown in the recent work by Voshage and Hintenberger (Ref. 54) that the K^{40} in iron meteorites is essentially of cosmogenic origin. This is a contradiction of the assumption of normal isotopic composition of potassium, which is the basis of the preceding work. If we take this circumstance into account when calculating age, then the value of the age of the material in iron meteorites according to the K/Ar method would be increased considerably. Here, too, it seems that further painstaking investigations are necessary.

As may be seen from the data presented here, the problem of the direct determination of the age of the material in iron meteorites remains an open question at present and requires the continuation of investigations along different directions.

The Content of Isotopes of Cosmogenic Elements

As stated previously, both stable and unstable isotopes of different elements appear in meteorites as a result of nuclear reactions of different types between the elements contained in the meteoritic material and high-energy cosmic particles.

At present the following isotopes of cosmogenic elements have been discovered and their ratios determined in iron and stone meteorites: H^3, He^3, He^4, Li^6, Be^{10}, Ne^{20}, Ne^{21}, Ne^{22}, Al^{26}, Ar^{36}, and Ar^{38}; in addition, the isotopes Ar^{39}, K^{40}, K^{41}, Sc^{45}, (Ca^{46}) have been found

and the presence of the isotope Mn^{53} has been theoretically assumed in iron meteorites.

Knowing the amount of cosmogenic elements in meteorites and the rate of their accumulation, one can determine the time the meteorite has been irradiated with cosmic ray particles.

In view of the fact that cosmic irradiation of the principal mass of meteoritic material is possible when the meteoritic material is in the form of small bodies, the time of irradiation should be counted from the time of the splitting of large bodies into fragments. This "age" is sometimes called the cosmic or radiation age of meteorites. We shall simply call it the age of meteorites, as distinguished from the age of the meteoritic material which was discussed in the preceding section.

In order to determine the age of meteorites it is essential to know the amount of stable isotope (denoted with the letters s. i.) of a cosmogenic element whose rate of accumulation is determined by the amount of the unstable isotope associated with it (denoted by the letters u. i.) with a sufficiently short half-life. The methods for determining the age of meteorites by u. i./s. i. pairs have been developed in this way. Such pairs are, for example, H^3/He^3 and Ar^{39}/Ar^{38}, depending on what is to be distinguished and the method for determining the age of meteorites.

At present some data on the age of stone and iron meteorites have been obtained with these methods. Using the H^3/He^3 method, Begemann, Geiss, and Hess (Ref. 55) found the age of the Norton County achondrite to be 240 - 280 million years while Geiss, Oeshger, and Signer (Ref. 56) used the same method to find the age of the Monte das Fortes chondrite to be 50 million years. Using the H^3/He^3 method Fireman and Schwartzer (Ref. 57) found the age of two iron meteorites to be 900 and 1700 million years. The figures obtained by different authors on the age of the Sikhote-Alin' iron meteorite are interesting. Using the quantity of He^3 as a basis, A. P. Vinogradov and others (Ref. 50) evaluated the age of this meteorite at about 1400 million years. Fireman (Ref. 58) used the Ar^{39}/Ar^{38} method (the Ar^{38} content was determined indirectly by the amount of He^3) to find the age of the meteorite to be about 500 million years; recently E. K. Gerling and L. K. Levskiy (Ref. 59) found the age of the meteorite to be 900 ± 50 million years by using the H^3/He^3 method

and 430±50 million years by using the Ar^{39}/Ar^{38} method.

Determination of the age of meteorites by their content of only one cosmogenic element (He^3, Ar^{38}, Ne) as done by certain authors, apparently yields approximate results.

It is possible to draw the preliminary conclusion from the restricted amount of available data that the fragmentation of large bodies which constituted the origin of meteorites took place tens and hundreds of millions of years ago: that is, considerably later than the formation of the meteoritic material.

It is possible to establish the time of the fall of ancient meteorites on the earth by determination of cosmogenic elements. It is necessary to have comparative data on the ratio of unstable isotopes with different half-lives or unstable and stable cosmogenic isotopes for this purpose.

For example, Ehman and Kohman (Ref. 60) found from the value of the Be^{10}/Al^{26} ratio in the Odessa iron meteorite that this meteorite fell less than one million years ago. Fireman (Ref. 58) established a very low Ar^{39}/He^3 ratio in the Carbo iron meteorite and concluded that this meteorite fell more than 1500 years ago.

Thus, a study of the chemical and isotopic composition of meteorites permits one to obtain a rough idea of the evolution of meteoritic material:

1. Formation of the elements — $7 \cdot 10^9$ to $5 \cdot 10^9$ years.

2. Solidification — $4.5 \cdot 10^9$ to $4 \cdot 10^9$ years.

3. Thermal changes — $4 \cdot 10^9$ to $1 \cdot 10^9$ years.

4. Fragmentation of large bodies — 10^9 to 10^7 years.

5. Falls of meteorites on the earth — 10^6 years.

II

Studies of the isotopic and chemical composition permit one to approach the solution of some problems in the movements of meteor bodies in the earth's atmosphere.

Because of the presence of the depth effect of distribution of cosmogenic isotopes in meteorites discovered by a number of authors, the study of the distribution of these isotopes through the entire meteorite is of great interest.

In view of the fact that the shape of the isoplets (lines of like content) of cosmogenic elements in cross-sections of meteorites or corresponding surfaces of its volume corresponds to the original shape of the meteorites, it is possible to determine the shape and dimensions of meteorites prior to their entry into the atmosphere and to evaluate the loss of mass during the passage of the meteor through the terrestrial atmosphere. The work done by Fireman (Ref. 61) on the distribution of He^3 in the maximum cross-section of the Carbo iron meteorite and similar work by Hoffman and Nier (Ref. 62) on the He^3 and He^4 content in the Grant iron meteorite, showed that the parts of these meteorites that were found represent only a small portion of their original mass b⌐⌐ause of losses of mass, this being true also because part of the fragmeɪ ᴜₛ were not found.

Losses of the original mass of meteorites can take place as a result of several processes--fragmentation and pulverization in the earth's atmosphere and corrosion on the earth's surface.

In order to establish a physical theory of meteorites it is important to know the value of loss of mass of meteors during their passage in the earth's atmosphere. To accomplish this, it seems to be necessary to conduct painstaking investigations of fresh, orientated (not shattered in the earth's atmosphere) iron meteorites.

The study of the content of meteoric dust, which is in the form of microscopic spheres, is the next problem in this field. The application of precise methods of analysis has recently permitted determination of the composition of deep-water spheres which have been known for a long time. Smales, Mapper, and Wood (Ref. 63) used a method of radioactive analysis, then Castaing and Frederiksson (Ref. 64) used local x-ray spectral analysis to establish the cosmic nature of these particles, and also the possible means of their formation.

It would be interesting to continue these investigations as applied to meteoric dust gathered on the site of falls of meteorites, comparing their composition with the composition of the melted crusts on corresponding meteorites in order to reveal the mechanism of pulverization of meteoritic material on the atmosphere. The further development of this work should make it possible to deepen our knowledge in this branch of meteoritics.

III

Study of the chemcial composition of the products of the disintegration of large meteorites could provide evidence of certain phenomena

which take place during their fall to the earth's surface.

Thus, for example, the oxidized globules of meteoritic material on the site of the fall of the Arizona meteorite which were studied by Nininger (Ref. 65) have a composition which differs materially from the composition of this iron meteorite, which may be explained by remelting of their material in the explosion of the meteorite. It should be noted that chemical studies have not been adequately utilized in the solution of such problems.

IV

The existence of meteorites under terrestrial conditions is accompanied by their gradual decomposition from oxidation and other processes.

Study of the chemism of these phenomena constitutes an important task for investigators in the field of meteoritics. Much work has been done on such problems by Buddhue (Ref. 66), who has established some important features in the processes of oxidation and weathering of meteoritic material--the oxidation of ferrous iron and troilite in stone and iron-stone meteorites and losses of nickel in the oxides of iron meteorites.

In conclusion it should be stated that the present discussion of the general outlines of the problem does not exhaust the content of all investigations into the chemistry of meteorites, the number of which is increasing rapidly.

It is essential to bear in mind that only a combination of these investigations with the study of the structure and different properties of meteoritic material along with data from astronomy, geology, and other sciences will permit drawing conclusions on the nature of meteorites and studying the phenomena associated with them.

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III.   THE PROBLEM OF TEKTITES AND SILICA-GLASSES

by G. G. Vorob'yev

Russian Text Pages 26-62.

In 1900 the well-known geologist and naturalist Franz Suess introduced the term tektite, which he used to designate unusual forms of glass which had been found in Bohemia, Moravia, Australia, on Billiton Island and other islands of the Dutch East Indies.
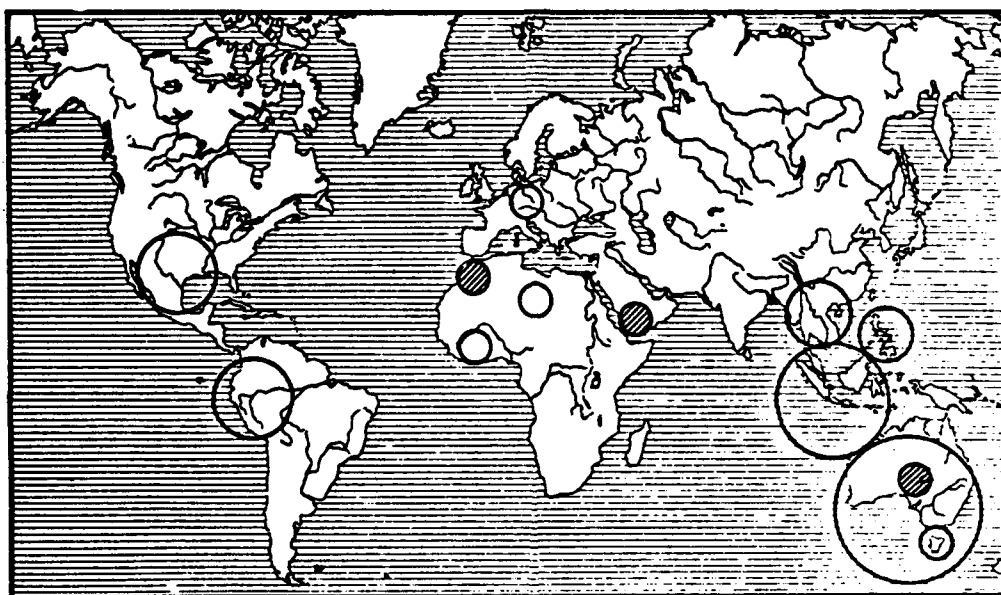
Figure 1.   Map of the distribution of tektites (regions of meteorite craters with impactite are cross-hatched).

Suess wrote: "I chose the general term tektites in accordance with a characteristic property of the entire group of bodies which, in contrast to other meteorites, are completely melted masses (τήκεζυ - the melting of metals and other solids, τηκτος - melted)" (Ref. 1).

Since that time tektite and tektite-like bodies have been found in Indochina, in the Philippines, in Africa, and in North and South America (Figure 1). They have acquired local names in each region, these names being justified by some territorial difference in spite of their general similarity (Table 1).

Charles Darwin, who was first to describe tektites in the Southern Hemisphere, called them "volcanic bombs" (Ref. 3).   Other early discoverers called them obsidianites at first (Refs. 4, 5), or simply

Region	Name	Synonym	Remarks
Czechoslovakia (Bohemia and Moravia)	Moldavite	Bottlestone, pseudo-chrys-olite	Bottle-like stone
		vltaviny	Along the Vltava River (ancient name of Moldau River)
Australia and Tasmania	Australite		(Refer to (Ref. 2) for aboriginal names)
Tasmania	Tasmanite	Darwin glass	
Indonesia and Malaya	Billitonite		On Billiton Island
Indochina, Southern China, and Hainan Island	Indochinite		
Philippines	Philippinite	Rizalite	In Rizal Province
Egypt (Libyan Desert)	Libyte	Libyan glass	
Peru and Boliva	Americanite		
United States (Southern States)	Bediasite		
Sweden	Schonite		

Table 1. Local Names and Synonyms for Tektites.

obsidians (Refs. 6-8). Glass was discovered in a number of regions
which differed noticeably from tektites even though they resembled tek-
tites somewhat; these were called silicate glasses (Refs. 9, 10). The
third group of glasses (they were also called silica-glasses or more
rarely impactites) are encountered in meteor craters and are fused rock
(usually sand or sandstone) formed by the fall of meteorites (Refs. 11,

12). Fulgurites, which are formed by lightning striking rock and which consist of fused quartz (lechatelierite), are apparently close to impactite in a genetic sense. Attempts have been made to compare fulgurites with moldavites in the literature (Ref. 13). In 1912 Gregory advanced the theory of atmospheric origin of fulgurites--atmospheric dust being fused by lightning (Ref. 14), which brings them closer to all tektites, particularly in connection with the well-known Spencer theory, which we shall discuss later.

Thus, the nomenclature of all natural fused glasses can be presented in the following form:

     I. Tektites, in the narrow sense, glasses of original form with a certain surface structure (sculptured);

     II. Silica-glass, in the narrow sense, amorphous glasses found on the earth's surface;

     III. Impactite, silica glass found in meteor craters.

     IV. Fulgurite.

This classification which stems from modern scientific data is still complicated by the fact that it is not always possible to set up clear-cut bounds between these groups.

Tektites and silica glasses have not been discovered anywhere in the Soviet Union. This fact can give rise to some perplexity in view of the large area of this country and the numerous finds which have been made in other countries. Apparently (this opinion is that of Ye. L. Krinov), the reason for this is that nobody has undertaken special searches for tektites in this country; unfavorable geological and geographical conditions hamper mass finds and random finds can lead to misunderstanding, since fragments from tektites and silica-glass remind one of ordinary glass and slag. Due to the almost complete lack of literature on this subject in the Russian language, our geologists have been completely uninformed on this problem, and in the best case (with small-scale surveys) might take tektites to be volcanic glass, as geologists in the United States have done in the past.

The idea of popularizing the tektite problem in the USSR was expressed for the first time by V. I. Vernadskiy. Acting on his advice, Ye. L. Krinov published the first survey in the Russian language on this subject in 1946 in the journal Priroda (Nature). Since then nothing has been done in this direction in spite of the fact that a number of works on individual problems involving tektites have appeared in the Soviet scientific press (Refs. 16-22).

This article, which was completed at the recommendation of Ye. L. Krinov, is a detailed scientific survey which can serve as a basis for popular surveys for a wider circle of readers--geologists and specialists in regional studies.

Moldavites

The first finds of tektites were made in Czechoslovakia. According to information available to us, local inhabitants began to find them not later than the first half of the 18th Century in river beds and to polish and to use them as ornaments.

In 1788 Jozef Mayer reported (apparently this was the first printed work on tektites): "Beautiful fragments of green masses of glass equal to granite in hardness, very pure and transparent, usually with a splendid dark-green color, and sold as chrysolites are often found near Thein on the Moldau, or Moldauthein (in Czechoslovakia - G. V.). I have not seen any shape in them, they are amorphous in the form of round pebbles and stones; now they are found only in these forms in scattered fragments in fields and in drainage ditches. The fragments are very frequently larger than a pigeon's egg and cane heads one inch wide and up to two inches long can be cut from some samples." (Ref. 23). The author called them "imitation chrysolites" and classed them with glassy lavas.

Somewhat later Johann Lindaker (Ref. 24) directed attention to the characteristic sculpture (half-moon shaped furrows) in these bodies and advanced several theories as to their origin: ejected by volcanoes, burning coal or by some artificial means (waste products from smelters or glass factories).

The first chemical analysis was made by Klaproth (Ref. 25). He was first to introduce the term pseudo-chrysolite.

In 1823 August Breithaupt (Ref. 8) called moldavite"bottlestone" and classed it with obsidian glass, after pointing out that they differed from real chrysolite in their flow structure.

Thus, by the 1830's, moldavite had acquired several names: Bohemian chrysolite, water chrysolite, chrysolite obsidian, pseudo-chrysolite, and bottlestone. The name moldavite (for the Moldau River), which has displaced all other names, was introduced in 1836 (published in 1840) by Zippe (Ref. 26). He wrote: "This mineral is found in flat, often elongated, large-grained and pine cone-shaped forms, resembling amber, with unusual depressions and striated surfaces. The color is dark, olive-green, at times merging into dark green; it is etched on the outside, with exceptional conchoidal fracture on the inside, and one observes wavy lines from impurities when light is shone through the glass.

This interesting modification of pyrodoxic (Transliterated) quartz differs from fused obsidians found in volcanic regions in color and good transparency..., even though similar fragments but with shapes not so flat are found in Hungary, and samples with a similar surface are found in Mexico." At the same time, the author emphasized that wholly identical geological specimens had not been described anywhere else up to that time.

Lively discussions on the origin of moldavite developed in the 1880's and 1890's. As early as 1832 Erdmann reported (Ref. 27) that it was difficult to melt moldavites, and that they became discolored when this was done. Experiments in melting moldavite were repeated in Brno by Professor Makowsky (Refs. 28-30), who discovered a rainbow iridescence under prolonged heating. These facts combined with the characteristic color, the lack of microscopic inclusions, and the fact that moldavites were found in youthful deposits in nonvolcanic regions, finally caused Makowsky to separate them from the obsidian group and to associate them with the products of old glass factories. Franz Dvorsky, a professor at a higher school in Trebitsch who discovered moldavites in Moravia in 1878, opposed (Ref. 31) Makowsky, stating that there had been no old glass factories in the regions where moldavites were found, but, on the contrary, moldavites were not found in the vicinity of old glass factories. These bodies were usually concentrated in quartz gravel at a depth of 2-5 meters in a hilly plain at levels of 50-100 meters above the level of the river, at times within the limits of floodplains too. Finds of moldavites along the beds of ancient river systems indicated that the time of their formation predated any form of glass production. Dvorsky's opinion was confirmed by Wenzliczke (Ref. 32) and Habermann (Refs. 33, 34), who published new chemical analyses and directed attention to the difference in ratios of basic oxides and melting points of glasses and moldavites. In defending Makowsky's position, Rzehak (Ref. 35) noted that the melting point of several artificial glasses can change noticeably with time. He changed his mind later (Ref. 36) and was first to suggest the probability of meteoritic origin of moldavites. According to F. Suess (Ref. 1), the characteristic sculpture of moldavites (and all tektites) was formed during their passage through the atmosphere.

The work done in subsequent decades has been directed essentially toward geological locations, the sculpture, and chemical composition of moldavites. Professor Dvorsky (Ref. 37), who was the first to give a thorough description of their form, noted the characteristic paraganesis of the moldavite; from Moravia: in gravel, with different modifications of quartz, at times with tourmaline, apparently of vein origin; in one place the gravel was covered with a layer of silicified limestone with seashells. Prior to this Woldrich (Refs. 38, 39) reported on three new finds of moldavites in Radomilitz (near Budweis) under a 50-centimeter

layer of clay soil in brownish-yellow conglomerate gravel lying in Ter-
tiary sands of an upper lignite formation. The age of the gravel was
determined as Pleistocene to Tertiary. Somewhat later Janoschek (Ref.
40) reliably classed the intruding rock of the tektites of Moravia as
Helvetian (Middle Miocene).

In this connection, the report of Doctor Beyer on the finding of
moldavites in Paleolithic loess at Willensdorf Station near Spitz on the
Danube is of interest. Thus, as Suess wrote, "The cave people used them
for tools." (Ref. 1).

In 1928, Hanus developed the following classification after study-
ing the sculpturing of moldavites:

1) hemispherical depressions; 2) ellipsoidal depressions; 3)
deep folds, "troughs" (circular and polygonal); 4) wrinkles (circular
and polygonal).

In 1936 Oswald (Ref. 42) established the basic indices of differ-
ences between the moldavites of Moravia and Bohemia on the basis of
these criteria and also by studies of other properties. The following
were characteristic of the first: a greasy or glass luster; simple
shapes, for the most part spherical and shapes of revolution, or ellip-
soidal shapes without deep surface sculpturing; the weight of some sam-
ples reached 235 grams. In the second case the luster was somewhat dull,
the shapes and sculpturing were more varied, and with weights up to 87.5
grams.

In this article the author included a map of old and new finds of

moldavites in Moravia and Bohemia--between 14 and 17° East longitude. A
similar map was published later (Ref. 43).

The first analysis by Klaproth into four components (SiO_2, Al_2O_3,

Fe_2O_3, CaO) (Ref. 25) was followed by a large number of complete chemi-

cal analyses of moldavites: by Hauer (Refs. 44, 45), John (Refs. 46,
47), Hanus (Ref. 48), Novacek (Ref. 49), Lacroix (Ref. 50), and others
(Refs. 22, 27, 32, 51, and 52). In 1958 G. G. Vorob'yev made a complete
quantitative spectral analysis of ten samples for 14 components (exclud-

ing SiO_2, K_2O, and H_2O).

According to all these data, moldavites are characterized by the
following basic composition (Table 2).

Oxides	Content, Weight Percent	Nbr. of Determinations		Oxides	Content Weight Percent	Nbr. of Determinations
SiO_2	74.91-88.50	24		CaO	0.76-4.67	33
TiO_2	0.32-1.8	18		MgO	0.22-2.65	32
ZrO_2	0.01*-0.05	13		BaO	0.29-0.86	10
Al_2O_3	5.10-13.80	32		SrO	0.02**-0.1	11
Fe_2O_3	0.00-2.61	10		Na_2O	0.23-2.45	30
FeO	0.95-3.36	32		K_2O	2.20-3.76	18
MnO	Traces -1.25	26		H_2O	0.02-0.20	10

* According to data from Hevesy and Wuertstlin (Ref. 53).

** According to data from Pinson (Ref. 85).

Table 2. Limits of the Chemical Composition of Moldavites

In addition, moldavites contain (in percent): vanadium 0.0018-0.0041 (10 determinations (Ref. 22)); chromium 0.002-0.006 (26 determinations (Refs. 22, 54, and 55)); nickel 0.001-0.003 (26 determinations (Refs. 22, 54, and 55)); cobalt 0.00064 (Ref. 17); gallium up to 0.002 (10 determinations (Ref. 22)); boron up to 0.002-0.003 (16 determinations (Ref. 55)); lithium 0.001-0.002 (Ref. 56); uranium 0.00015-0.00016 (2 determinations (Ref. 60)); beryllium $n.10^{-5}$ (Ref. 22); rubidium 0.01 (Ref. 85).

Gas inclusions are (percent volume): CO_2-12.6; CO-33.1; H_2-41.1 CH_4-traces; O_2-0.6 (Ref. 61); when converted to 100 percent by volume of the three basic components: CO_2-15; CO-38; H_2-47. According to other data (Ref. 51), these converted values are: CO_2-17; CO-63; and H_2-20. Thus, the amount of CO and H_2 in the gases included in moldavites can vary sharply.

Schonites

After this discussion on the origin of moldavites, a report appeared in the literature (Ref. 64) on the discovery of strange fragments of dark green glass with a specific gravity of 2.707, a dull luster and a shagreen surface at Hof Koelna (Starbi, Kristianstad Province) in Southern Sweden which could be identified with moldavites. A mineralogical study was made of them in 1909 (without chemical analysis) (Ref. 55). Nothing was reported of them since that time. Therefore schonite is provisionally classed by some authors with tektites or is taken to be industrial glass.

Australites

Although Czechoslovakia (or more precisely, Bohemia and Moravia) is a comparatively small but concentrated region of abundance of tektites, the Australian continent can be called a unique region of the earth in this respect.
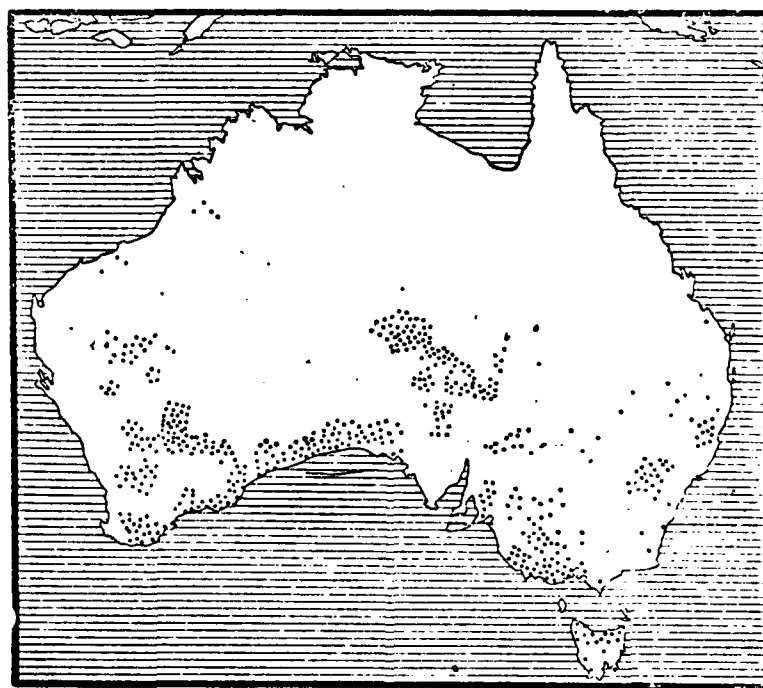
Figure 2. Map of the distribution of australites
(according to Baker (Ref. 2)).

The points where tektites have been found, according to the map presented here (Figure 2) give an idea of the true scale of the processes which led to the appearance of these puzzling bodies.

As pointed out here, the first report on australites was made by Charles Darwin. There is no doubt that the aboriginal population of Australia knew of them for many centuries. We find the following words in the writings of Fenner, a well-known student of australites: "It was not Charles Darwin, but the aborigines who were first to theorize about australites. The natives of the interior of the country (Dieru and neighboring tribes) know them under the name "cora" and "muramura" together with associated legends ... of "radiant eyes" and of "emu eyes". Their origin was based on the views of men of the stone age who believed in their might ... and ascribed attributes of mysticism and magic to them, usually for healing and bringing rain." (Ref. 66). The Australian ethnologist Mountford wrote that, "Australites are the invariable possession of "nungari" (medicine men) which resemble quartz crystals and which the healers of the southern tribes use as medicine. These stones, meteorites, serve different purposes in the hands of the "nungari". For example, when they are introduced into the body they restore lost strength, or they protect property like a watchdog, they point out where the enemy is, and they help to point out fellow tribesmen ..." Later the author told of one aborigine who had obtained an australite from a healer to be introduced under the skin of his solar plexus in order to become a healer himself (Ref. 67).

The interesting work by Baker on the role of australites in the lives of the aborigines (Ref. 2) described the ceremonies connected with australites due to their attributes of medicine, death, punishment, happiness, witchcraft, et cetera, that result from the exceptional (extraterrestrial?) origin of these stones.

One of the early descriptions of australites (obsidian bombs) in the auriferous alluvial deposits of New South Wales was given in 1855 by Clark (Ref. 68). A geological study by Streich (1893, (Ref. 69)) explained the origin of "obsidian bombs" by volcanic activity. In the same year Stelzner (Ref. 70) compared moldavites with these "bombs". He explained finding the latter in gravel deposits as the result of transportation by water and the presence of the characteristic sculpturing as the result of chemical and mechanical processes. Several years later Walcott (Ref. 6) gave obsidian bombs the name "obsidianites", considering them to be meteorites which had acquired their form during their passage through the atmosphere.

However, Dunn (Refs. 71, 72), who studied the structure of australites under a microscope with crossed Nicol prisms for the first time in 1908, continued to develop the theory of their volcanic origin, assuming a variant in the formation of porous bombs in volcano craters subsequently ejected into the air. In rejecting this theory, Summers (Ref. 73) pointed out that the results of painstaking studies of the analyses would not permit considering australites either as volcanic or

as artificial bodies. There are no bedrocks which resemble australites in Australia; nevertheless, the latter do vary territorially in a wholly regular pattern as regards content.

Research done in the first decades has permitted the collection of a large amount of material on australites. Charles Fenner (Ref. 66) studied 11,946 samples in museums and private collections. It was established through these summary data that australites are found in alluvial gold and tin-bearing ore regions, and on the surface in other places. In reflected light the samples are tar-black with transitions from brownish amber to bronze-green. Their weight varied from 0.15 to 218 grams (average weight 0.934 grams).

In January 1953, Baker (Ref. 74) found 46 points of accumulation of tektites within the bounds of three areas (150, 8,000-9,000, and

30,000 square miles) in the coastal region between $142^{\circ}30'$ and $143^{\circ}20'$ East longitude. The number of finds were 1,877, 7,184, and 3,920 respectively, which meant a density of concentration of 12.5, 0.8, and 0.13 per square mile. In three other regions--Nirranda, Port Cambell, and Moonlight Head the number of finds were 370, 1,487, and 20; the total weight of the samples was 668.396 grams, 830.322 grams, and 51.05 grams; the extreme weights were 0.090-55.100 grams, 0.054-56.482 grams, and 0.34-25.869 grams; the average weights were 1.826 grams, 1.549 grams, and 3.403 grams.

The specific gravity of 53 samples from Southwestern Victoria (Baker (Ref. 74)) varied from 2.66 to 2.83 and the index of refraction was 1.575.

Baker classified australites by their shape as lenses, bullets, ovals, boat-shaped, canoe-shaped, bells, tears, round and elongated nuclei, oval plates, spheres, and fragments of these shapes. Other works by Baker are also devoted to the study of these shapes, the sculpturing, and other physical properties. The author believes that the formation of the latter occurred during the flight of the tektites through the earth's atmosphere (Refs. 76-80). These conclusions are close to the opinion of a well-known modern student of tektites, Cassidy, who considers them (in particular, australites) as glassy meteorites with primary shapes of revolution and secondary details due to fusion during their passage through the earth's atmosphere.

Table 3 gives the chemical composition of australites according to data from Summers (Refs. 73 and 82), Baker (Refs. 74 and 75), and other authors (Refs. 83 and 84).

Oxides	Content, Weight Percent	Nbr. of Determinations	Oxides	Content, Weight Percent	Nbr. of Determinations
SiO_2	47.54-79.51	21	SrO	Up to 0.03[*]	6
TiO_2	0.08-3.38	19	Na_2O	0.91-3.54	21
ZrO_2	0.01	1	K_2O	1.24-3.02	21
Al_2O_3	9.97-16.49	21	H_2O^+	0.01-1.10	19
Fe_2O_3	0.20-5.37	21	H_2O^-	Up to 0.44	19
FeO	2.97-11.51	29	NiO	Up to 0.06	17[**]
MnO	Traces-0.42	12	P_2O_5	Up to 0.35	11
CaO	1.48-8.56	21	Cl	Up to 0.12	6
MgO	1.35-7.99	21			

[*] According to data from Pinson and others (Ref. 84).

[**] According to data from Preuss; 0.003-0.005 percent NiO (Ref. 55).

Table 3. Limits of the Chemical Composition of Australites.

In addition, australites contain (in percent): rubidium 0.01 (2 determinations (Ref. 85)); chromium 0.006-0.11 (8 determinations (Ref. 55)); boron 0.001-0.002 (8 determinations (Ref. 55)); vanadium $n \cdot 10^{-3}$ (Ref. 86); copper $n \cdot 10^{-4}$ (Ref. 86); thorium $9.19 \cdot 10^{-4}$ (Ref. 87); uranium $1.6-2.4 \cdot 10^{-4}$ (3 determinations (Refs. 60, 87). Gas inclusions are (in percent volume): CO_2 - 6, CO - 92, H_2 - 1.5, H_2O - traces (Ref. 57).

Tasmanites

Tektite-like bodies with a very high SiO_2 content with correspondingly low specific gravity and index of refraction have been discovered in Tasmania along with australites. They appear in the

literature under three synonomous names: tasmanites, queenstownites, and "Darwin glass".

They were reported for the first time by F. Suess in 1914, (Ref. 51). The most detailed descriptions were given by David, Summers, and Ampt (1927, (Ref. 89)).

Tasmanites are found in the Jukes Darwin ore field (region in the Darwin and Queenstown Mountains) along with quartzite gravel, in many places at a depth of 9-18 inches under a peat layer of post-glacial age.

They are not found in the city of Darwin itself (1300 feet altitude), which is explained by the action of the glacier which carried the glass down and concentrated it in the valleys. An average of 1/4 to 1/2 units of the glass are found per square foot of gravel bed. The color varies from a dark smoky color to almost black to blackish-green with separate almost white sections due to a large quantity of pores.

We have taken four chemical analyses of tasmanites from cited sources (Table 4).

Oxides	Content, Weight Percent	Nbr. of Determinations	Oxides	Content, Weight Percent	Nbr. of Determinations
SiO_2	86.34-89.81	4	MgO	0.58-0.92	4
TiO_2	0.51-1.24	4	Na_2O	0.01-0.15	4
ZrO_2	Traces-0.11	2	K_2O	0.87-1.36	4
Al_2O_3	6.13-8.00	4	H_2O^+	0.43	1
Fe_2O_3	0.19-0.63	3	H_2O^-	0.03	1
FeO	0.89-2.3*	4	$H_2O^{\pm}$	0.36-0.46	2
MnO	Up to 0.01	4	P_2O_5	Traces	1
CaO	Up to 0.17	3			

* According to data from Preuss (Ref. 55).
  In addition, Preuss discovered: Cr_2O_3 0.035 percent and NiO 0.04 percent.

Table 4.   Limits of the Chemical Composition of Tasmanites.

Billitonites and Java Tektites

Tektites collected over a large area of Southeastern Asia were studied at the same time as australites. The first find in this area was made on Billiton Island (between Borneo and Sumatra). In 1879 the Dutch scientist Van Dijk reported (Ref. 7) that Chinese laborers working on tin deposits on an ancient gravel bed had discovered bits of obsidian which were taken for black diamonds at first. Although he called these objects "Billiton obsidians", he rejected their volcanic origin. Another Dutch investigator, the geologist Verbeck (Refs. 90, 91), suggested that they were ejected from lunar volcanoes.

Oxides	Content, Weight Percent	Nbr. of Determinations	Oxides	Content, Weight Percent	Nbr. of Determinations
SiO_2	69.32-73.73	9	MgO	2.16-4.05	9
TiO_2	Traces-1.10	8	Na_2O	0.77-2.46	9
Al_2O_3	11.33-14.30	9	K_2O	1.90-2.76	9
Fe_2O_3	0.06-1.07	8	H_2O^+	0.14-0.25	2
FeO	4.46-6.81	16	H_2O^-	0.06-0.14	4
MnO	Traces-0.32	9	P_2O_5	0.06-0.19	2
CaO	2.35-3.92	9			

Table 5. Limits of the Chemical Composition of Billitonites and Java Tektites.

In addition, Java tektites contain (in percent) (Ref. 99); strontium 0.08; BaO 0.01; Sc_2O_3 0.005; Ga_2O_3 0.001; Y_2O_3 0.001; Ge_2O_3 0.0005. According to Preuss' data (6 determinations (Ref. 55)), the following are found in billitonites (in percent): Ba_2O_3 0.003-0.006; Cr_2O_3 0.045-0.063; NiO 0.03-0.044. De Ment (Ref. 100) also discovered silver and gold while Friedman (Ref. 60). found uranium (billitonite 0.00014 percent, Java tektites 0.00015 percent). The solid sublimate extracted from billitonite contained 5 mg/kg NH_4CL and 60 mg/kg (Na, K)Cl; the gas content

(in percent volume); CO_2 - 43, CO - 44, H_2 - 12.8, N_2 - traces, SO_2 - 0.2, H_2S - none, and O_2 - none.

In 1898 similar bodies were found on Bunguran Island (in the Natuan Archipelago off the coast of Borneo) (Refs. 12, 193), then on Borneo (Ref. 14) and other islands, also on the Malayan Peninsual (Ref. 4, 5); they received the general name billitonites.

All billitonites are characterized by a black color, rounded shapes, frequently in the form of spheres, with fantastically sculptured figures and deep furrows. Krause (Ref. 92, 93) was first to study these furrows and took them to be proof of the extraterrestrial origin of billitonites.

The fact that billitonites are called "moon spheres", "lightning stones", and "thunder stones" throughout all of Indonesia is noteworthy.

Tektites with somewhat different figures and composition were described on Java (Refs. 95, 96).

Published data from chemical analyses of billitonites and Java tektites are presented in Table 5.

Indochinites

In 1929 (Refs. 98, 101) the well-known French mineralogist Lacroix reported the discovery of a large bed of tektites in Indochina. In 1932 he published a well illustrated book (Ref. 50) in which he included a map of the distribution of tektites over the territory of Cambodia, Thailand, Laos, and adjacent regions of China, including Hainan Island.

Table 6. Limits of the Chemical Composition of Indochinites.

Oxides	Content, Weight(Percent)	Number of Determinations
SiO_2	70.40-76.64	23
TiO_2	0.62-2.2	29
Al_2O_3	11.36-15.3	29
Fe_2O_3	0.06-0.37	4
FeO	3.4-5.63	31

Oxides	Content, Weight (Percent)	Number of Determinations
MnO	0.09-0.32	29
CaO	1.34-3.92	29
MgO	0.22-2.7	29
BaO	0.10-0.22	6
SrO	0.01*-0.07	9
Na_2O	0.90-2.00	29
K_2O	1.84-2.80	23
H_2O^+	Traces-0.22	14
H_2O^-	0.04-0.26	19

* According to data from Pinson and others (Ref. 85).

Table 6. (Continued)

In addition to these basic elements in indochinites, the following have been observed (in percent): zirconium 0.0040-0.027 (6 determinations (Ref. 20)); chromium 0.0085-0.22 (18 determinations (Refs. 20, 55, and 102)); nickel 0.001-0.023 (14 determinations (Refs. 20 and 55)); vanadium 0.0054-0.010 (6 determinations(Ref. 20)); gallium 0.001-0.01 (6 determinations (Ref. 20)); copper 0.0011-0.0029 (6 determinations (Ref. 20)); cobalt 0.00036-0.0014 (7 determinations (Refs. 17, 20)); uranium 0.00011-0.00030 (8 determinations (Refs. 60, 104)); rubidium 0.011-0.013 (3 determinations (Ref. 85)); and beryllium $n \cdot 10^{-5}$ (Ref. 20).

Indochinese tektites, which are called indochinites (Figures 3 and 4) have the shapes of disks, ellipsoids, spheres, fingers, drops, cones and sickles; the color is black (yellow and brown fragments); at times with a large number of pores. They are found in alluvial deposits, primarily of the Quaternary Period, on granites, dacites, basalts, crystalline shales, and various sedimentary rock of the Silurian, Devonian, and Triassic Periods. In 1935 Lacroix (Ref. 102) reported the discovery of several thousand fragments of a single enormous tektite in Lower Laos (the weight of several specimens reached several kilograms).

No actual relationship is known as yet between indochinites and billitonites, and Malayan tektites are associated with billitonites in a somewhat provisional manner. Some investigators are of the opinion

(Ref. 95) that the Java tektites occupy an intermediate position be-
tween billitonites and indochinites. Noticeable differences have been

Figure 3. Shapes of indochinites (from Lacroix
(Ref. 50)). One-half natural size.

established in the indochinite group itself, which permitted Lacroix to
separate two independent families--northern and southern indochinites.

According to data from archeological and ethnographic research,
tektites have been known in Indochina for at least 1,000 years before
our times (Bronze Age). The eyes of the gods in some ancient statuary
were made of polished tektites. In local folklore (in particular, on

Hainan Island (Ref. 103), indochinites are called "moon stones", "devils balls", and "feces of the stars".

Figure 4. Shapes of indochinites (from Lacroix (Ref. 50)). One-half natural size.

Generalizing these data, and taking into account all existing hypotheses of the origin of tektites, Lacroix conditionally accepted the meteorite hypothesis for indochinites.

Indochinites have been studied more thoroughly in chemical respects than other tektites. Lacroix published 23 analyses of indochinites in his work of 1935 (Ref. 102). In 1958 G. G. Vorob'yev (Ref. 20) made six complete spectral analyses of the basic and secondary components. The earliest analyses of the secondary components were made by Preuss (Ref. 55).

In connection with the fact that the nickel content (and that of certain other elements) varies territorially in indochinites, Preuss (Ref. 105) gives the following limits of NiO content for three regions:

Bo-Ploi (Transliterated)	0.006 percent
Hainan	0.002-0.004 percent
Cambodia	0.021-0.028 percent

On the whole, northern and southern indochinites contain, respectively (Ref. 106): 0.012 and 0.036 percent Cr_2O_3 and 0.0035 and 0.025 percent of NiO.

Philippinites

It is possible that the most exceptional region of abundance of tektites is the Philippine Islands where, according to Bayer, the best expert on philippinites, there are at least three fields of these bodies.

Students of philippinites, in addition to Bayer (Ref. 107, and other works, also manuscripts) include Lacroix (Ref. 97), Hodge-Smith (Ref. 108), Heide (Ref. 109), and Koomans (Ref. 110). The first report on philippinites was made by Selga (Ref. 111).

The first piece of unusual black glass was discovered in October 1926 on an archeological slope in Novaliches (Rizal Province). Bayer visited this place two years later with the Dutch scientist Overbeek. The latter identified the glass with the billitonites which were known at that time. Due to certain noticeable external differences (well-rounded pebbles with fine sculpturing), Bayer gave them the new name rizalites.

A second group of philippinites discovered on Busuang Island has a somewhat closer similarity with billitonites and particularly with southern indochinites. They differ from the former by less defined external shapes and clear-cut sculpturing "worm traces" (as in billitonites).

The third group was discovered in the vicinity of Manila--in the Santa Mesa region. The following are encountered here among ordinary rizalites: 1) gray glass with a characteristic obsidian internal structure and the shapes of ordinary tektites; 2) glasses of varied color-- from brownish violet to rosy red, without any internal structure; these are very similar to ordinary rizalites and differ from them in transmitted light; 3) greenish-hollow glass with the sculpturing of true rizalites. All three variants are mixed with true rizalites in a gray bed of gravel 10-20 cm thick lying on volcanic tuff (local name--adobe). The

tuff and gravel are covered in many places with a layer of soil and recent alluvial deposits.

The largest specimen of philippinite weighs 226 grams (6.5 x 6.2 x 5.2 cm) and is in the California University museum (Ref. 88).

Tektites have been known to the native population of the Philippines from great antiquity. Arrowheads and other tools were made of them in the stone age. The characteristic polish of tektites in graves of the Iron Age provides evidence of their use as amulets and talismans. Philippinites are now known by several local names: "taeng kulog" (feces of lightning), "taeng bituin" (feces of stars), and "batong-arao" (sun stones). Thus, folklore invariably emphasizes their extraterrestrial origin.

The chemical composition of philippinites (Refs. 97, 110) is given below.

Oxides	Content, Weight Percent	Nbr. of Determinations	Oxides	Content, Weight Percent	Nbr. of Determinations
SiO_2	70.66-71.64	4	MgO	2.23-3.65	4
TiO_2	0.63-1.04	4	Na_2O	1.21-1.66	4
Al_2O_3	12.08-13.52	4	K_2O	1.69-2.28	4
Fe_2O_3	0.59-2.03	3	H_2O^+	0.15-0.63	4
FeO	3.03-5.32	4	H_2O^-	Traces	1
MnO	0.08-0.16	4	P_2O_5	0.10-0.18	3
CaO	2.95-3.42	4			

Table 7. Limits of the Chemical Composition of Philippinites

Other elements in philippinites were determined (in percent): cobalt 0.00093 (Ref. 97); strontium 0.02 (Ref. 85); rubidium 0.01 (3 determinations (Ref. 85)); uranium 0.00017-0.00027 (5 determinations (Ref. 60)). Gas bubbles contained (in percent volume): CO_2-21, CO - 56, H_2-6, and H_2O-15 (Ref. 57).

Tektites From the Ivory Coast

David, Summers, and Ampt (Ref. 89), who had described "Darwin glass" in detail, expressed the idea in 1927 that all the finds of tektites were located along a circle of the terrestrial sphere from the southeast to the northwest due to the passage of the earth through a large swarm of meteorites. This idea became widespread at that time, particularly after new finds of tektites in Indochina and in the Philippines, which permitted connecting them with the tektite regions in Europe and Australia known at that time.

In 1934, however, Lacroix (Refs. 102, 112) described tektites beyond the limits of this imaginary circle--on the Ivory Coast in French West Africa.

The tektites which were found were very similar to billitonites in structure and color and had the following chemical composition:

Oxides	Content, Weight Percent	Nbr. of Determinations	Oxides	Content, Weight Percent	Nbr. of Determinations
SiO_2	68.00-76.56	3	MgO	2.88-3.60	3
TiO_2	0.60-0.80	3	K_2O	0.82-1.92	3
Al_2O_3	11.54-16.46	3	H_2O^+	0.13-0.22	2
Fe_2O_3	3.99-6.64	3	H_2O^-	0.07-0.14	2
MnO	0.06-0.09	3	Na_2O	1.32-2.35	3
CaO	1.40-2.00	3			

Table 8. Limits of the Chemical Composition of Tektites from the Ivory Coast.

According to Friedman's data (Ref. 60), the uranium content is $9.1 \cdot 10^{-5}$ percent.

South American Tektites (Americanites)

Other finds of tektites were made in South America--in Peru (Ref. 113 - 115) and Colombia (Refs. 61, 116, and 117). In 1934 Martin called them "americanites" but this name soon became obsolete, since new

tektites were found in North America.

Franz Suess, who had developed a meteorite theory of the origin of tektites, strongly opposed classifying americanites with tektites. Actually americanites do differ sharply from moldavites, australites, indochinites, and billitonites. Specimens from Colombia have an unusual violet and reddish-violet color in transmitted light (in fact, reminding one somewhat of the color of the second variant of philippinites from Santa Mesa). The specimens from Peru are greenish-yellow with microinclusions of different minerals: andalusite, sillimanite, wollastonite, scapolite, sanidine, oligoclase-andesite, zircon, aegirite, ordinary and basaltic augite.

The chemical composition of americanite is also distinguished by certain unique features:

Oxides	Colombia (Cali)	Colombia (Tetilia)	Peru
SiO_2	75.87	76.37	70.56
TiO_2	Traces	0.11	0.05*
Al_2O_3	14.35	12.59	20.54
Fe_2O_3	0.22	0.26	Not Determined
FeO	Not Determined	0.48	0.1* } 0.96
MnO	" "	0.14	
CaO	0.00	0.79	0.78
MgO	0.29	0.17	0.11
Na_2O	3.96	3.36	3.42(3.5)*
K_2O	4.65	4.67	3.41(2.7)*
H_2O	0.33	0.97	0.83(p.p.p.)
SO_3	0.23	0.13	Not Determined
Sb_2O_3	Not Determined	0.07	Exists
P_2O_5	" "	0.02	Not Determined
Li_2O_5	" "	Not Determined	0.8*
BeO	" "	" "	(0.01-0.02)*

(Continued)

Oxides	Colombia (Cali)	Colombia (Tetilia)	Peru
B_2O	Not Determined	Not Determined	0.8^*
Ga_2O_3	" "	" "	(0.01-0.02)
As_2O_3	" "	" "	0.03

* According to data from spectral analysis.

Table 9. The Chemical Composition of Americanites
(Percent Weight).

In addition, the following were discovered in glasses from Peru by means of spectral analysis (in percent) (Ref. 113): Rb_2O 0.005; Cs_2O < 0.003; ZrO_2 ~ 0.001; V_2O_3 ~ 0.001; Cr_2O_3 < 0.001; NiO < 0.001; CuO 0.002; ZnO 0.005; HgO 0.002(?); GeO_2 0.005; SnO_2 0.003; PbO 0.001; the presence of Bi was established qualitatively; according to Friedman (Ref. 60), they contain 0.0018 of uranium. The composition of gaseous inclusions is the same as in moldavites (in percent volume): CO_2 - 27.1, CO - 24.4, H_2 - 35.3, CH_4 - 2.2, and O_2 - 1.1 (Ref. 61).

Tektites from North America (Bediasites)

The description of North American tektites is essentially that of Barnes (Ref. 119 - 121).

The first finds of bediasites were made in 1936 in Grimes County (Texas) by the geologist Ramsey, who reported this in a special report to the Bureau of Economic Geology in which he called them "obsidians". A total of 482 specimens was found from April 1936 through December 1938 in a region with coordinates $30°33'$ to $30°41'$ North latitude and $96°03'$ to $96°09'$ West longitude. Some of them were collected as "black diamonds". Oil geologists called them "volcanic glasses". The 79 specimens which were studied showed a variation in weight of 0.5 to 59.4 grams (average 15.57 grams), the specific gravity was 2.3742, and the average index of refraction in sodium light was 1.497.

The results of a chemical analysis of two specimens are presented

in Table 10.

Oxides	Specimen I	Specimen II	Oxides	Specimen I	Specimen II
SiO_2	73.52	77.76	CaO	0.06	0.04
TiO_2	0.87	0.76	MgO	1.38	1.19
Al_2O_3	15.88	13.30	Na_2O	1.30	1.41
Fe_2O_3	0.45	0.37	K_2O	1.73	1.97
FeO	4.64*	3.36	H_2O	0.08	0.02
MnO	0.01	0.01			

Table 10. The Chemical Composition of Bediasites
(Percent Weight).

*Nio, CuO, and CaO have not been found in bediasites. According to Friedman's data, the uranium content amounts to
0.00011-0.00024 percent (2 determinations).

Libyan Glass (Libyite)

The so-called Libyan glass (or silica-glass) occupies a special
place in the problem of tektites. This glass is found in the Libyan
Desert (Egypt) in the region $25°2'$ to $26°13'$ North latitude and $25°24'$
to $25°55'$ East longitude.

The southern part of this region intersects an old camel trail
from the Kufra Oasis (Cyrenaica) to Abu Miggar (Egypt). In 1810 a caravan tried to pass through it and died of thirst. Six years later a second attempt was made which ended unsuccessfully. On the second or third
day out on the trail numerous fragments of glass were discovered (Ref.
122). Borchardt, who studied them, took this glass to be fragments of
glazing from clay pottery.

Cleyton (Ref. 9) discovered glass in the same area in December
1932 and in 1934 Spencer, who participated in a special expedition,
toured the region and made a painstaking study of the conditions of deposition (Ref. 10). The following year Shaw (Ref. 123) and in 1938
Major Bagnold(Ref. 10) also found glass at a distance of more than 200

km from the original region, where they had apparently been transported by wandering Arabs or prehistoric men.

Libyan glass is concentrated together with remnants of human utensils in the form of fragments of irregular form weighing from several grams to 7.25 kg on the surface of the soil in corridors between ridges of sand dunes (Figure 5). The ridges reach a height of 300 feet with a width of 1 - 2 km and extend from north to south for more than 200 miles. The width of the corridors is from 2 to 3 km. The glassy fragments are scattered irregularly and form accumulations in places. A total of 111 fragments was discovered in one such spot measuring 2 x 2 meters.

A monolith of Nubian sandstone measuring 2 x 2.45 meters which was removed for testing contained only individual bits of glass at depths not exceeding 1.18 meters.
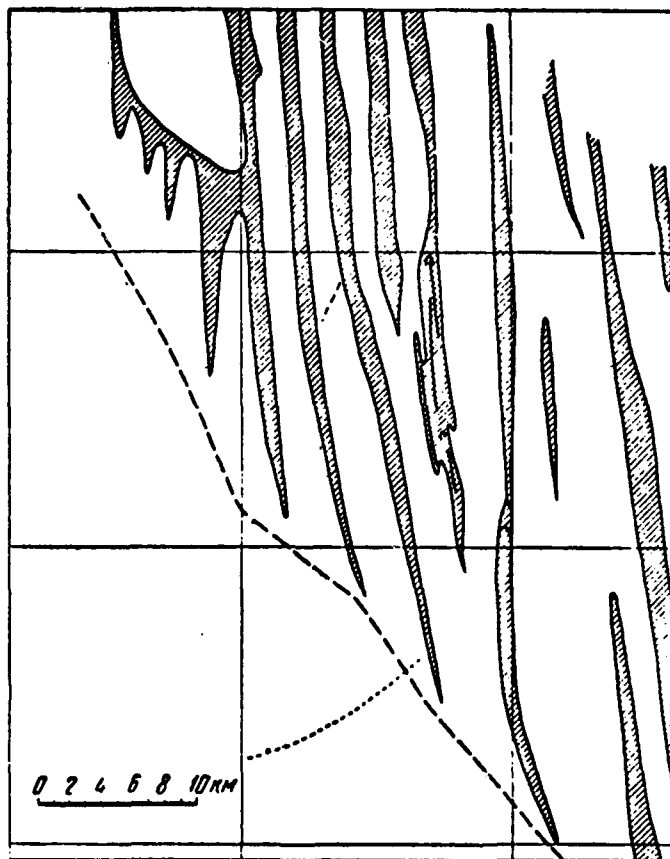
Figure 5. Corridors between dunes (cross-hatched areas) in which Libyan glass was found (from Spencer (Ref. 10)).

Oxides	Content, Percent Weight	Nbr. of Determinations		Oxides	Content, Percent Weight	Nbr. of Determinations
SiO_2	97.58-98.44	4		CaO	0.05(?),0.30-0.38	4
TiO_2	0.21-0.25	4		MgO	Traces-0.01	4
Al_2O_3	0.49-1.54	4		Na_2O	0.33-0.34	3
Fe_2O_3	0.11-0.54	4		K_2O	Up to 0.02	3
FeO	0.23-0.24	3		H_2O^+	0.03-0.05	3
NiO	Traces-0.032	4		H_2O^-	0.03-0.05	3
MnO	Traces	1				

Table 11.   Limits of the Chemical Composition of Libyan Glass.

Ramage also discovered Fe and small quantities of Ca, Sr, Mn, Ag, Li, Na, Pb, Ni, Ga in a 2.3 percent residue which was insoluble in hydrochloric and sulfuric acids with flame spectra (Ref. 10). Another investigator, Chapman, identified lines of Mg, Cu, Al, Ba, Ca, Fe, Pb, Mn, Ag, Si, Li, Ti, Ni, and Cd in the same residue by arc spectral analysis (Ref. 10). According to data from Preuss (Ref. 55), the Cr_2O_3 content in silica-glass

amounts to 0.035 percent and NiO 0.04 percent. Thus, 22 chemical elements were discovered in Libyan glass along with O and H.

Silica-Glasses from Meteoric Craters (Impactites)

The so-called impactites (from the English word impact, meaning blow, collision), silica-glasses from meteorite craters, have a definite similarity in respect to a number of characteristics with silica-glasses (libyite, tasmanite) on one hand, and with tektites on the other.

Studies of known meteorite craters: Henbury in Australia (Ref. 11), Wabar and Nejed in Arabia (Ref. 11), Aouelloul in the Sahara (Ref. 12), and other places showed that bits of silica-glass (Figure 6) with inclusions of iron spheres are found in the craters themselves and around them. Silicate rocks served as the material for the formation of the silica-glass.

Oxides	Australia (Henbury)		Arabia (Wabar)			Sahara (Aouelloul)			
	Sandstone	Silica-glass	Sandstone	Silica-Glass		Sandstone		Silica-Glass	
SiO_2	86.71	68.88	92.06	92.88	87.45	93.30	92.00	86.92	68.10
TiO_2	0.32	3.64	0.12	0.12	0.15	0.55	0.45	0.49	0.60
Al_2O_3	3.84	5.60	2.80	2.64	1.77	1.85	2.75	6.47	5.05
Fe_2O_3	2.84	8.46	0.60	0.23	0.28	0.45	0.75	1.16	1.45
FeO	0.46	7.92	0.19	0.53	5.77	0.05	0.05	1.72	1.45
NiO	None	0.28	None	None	0.35	None	None	0.019	0.025
CoO	- -	Traces	- -	- -	Traces	Not deter	Not deter	None	None
MnO	0.005	0.05	0.01	0.01	0.01	0.02	0.06	0.04	0.05
CaO	1.00	2.51	1.19	1.46	1.90	0.80	0.70	0.55	0.90
MgO	0.90	2.03	0.45	0.47	0.60	0.40	0.90	0.32	1.50
Na_2O	0.13	0.03	1.03	0.42	0.39	0.20	0.20	0.23	0.05
K_2O	1.15	1.43	1.04	1.61	0.58	0.10	1.00	2.05	2.05
H_2O^+	1.85	0.03	0.20	0.32	0.04	0.70	1.10	0.19	0.20
H_2O^-	0.82	0.05	0.22	0.11	0.08	0.10	0.14	0.10	0.20
P_2O_5	None	None	None	Traces	Traces	0.04	0.08	Not deter	0.06
CO_2	None	- -	0.58	None	- -	Traces	Traces	None	None
SO_3	Traces	- -	Traces	None	- -	- -	- -	- -	- -
Cl	None	- -	Traces	- -	- -	- -	- -	- -	- -

Table 12. Chemical Analyses of the Enclosing Rocks and
Silica-Glasses from Meteorite Craters
(Percent of Weight)

Remelting and penetration of meteoritic material result in the
regrouping of certain components: the SiO_2, Na_2O, H_2O, and SO_3 contents
decrease while the TiO_2, Al_2O_3, Fe_2O_3, FeO, NiO, CoO, and CaO contents
increase (Table 12). The specific gravity decreases somewhat in

accordance with this situation. The index of refraction of the glasses is 1.468-1.545.

Similar formations are observed in the vicinity of atom bomb explosions (for example, in Nevada) and are of great scientific interest.

A comparison of the properties and composition of impactites with silica-glasses and tektites (Refs. 9-11) permitted Spencer to develop a clever theory (Refs. 124-128) according to which all tektites are formed when rock spray caused by the impact of huge meteorites hardens in the air.

Some Comparisons

A quick comparison of data on tektites reveals similarity of specimens found in different regions of the earth. However, a more careful study shows some differing features, at times so important that the question arises as to whether certain formations can be classed as tektites and what should be understood to be included in that term in general. A comparison of all the special features of tektites is very important and will probably lead to a final solution of the question of the nature of these puzzling bodies.
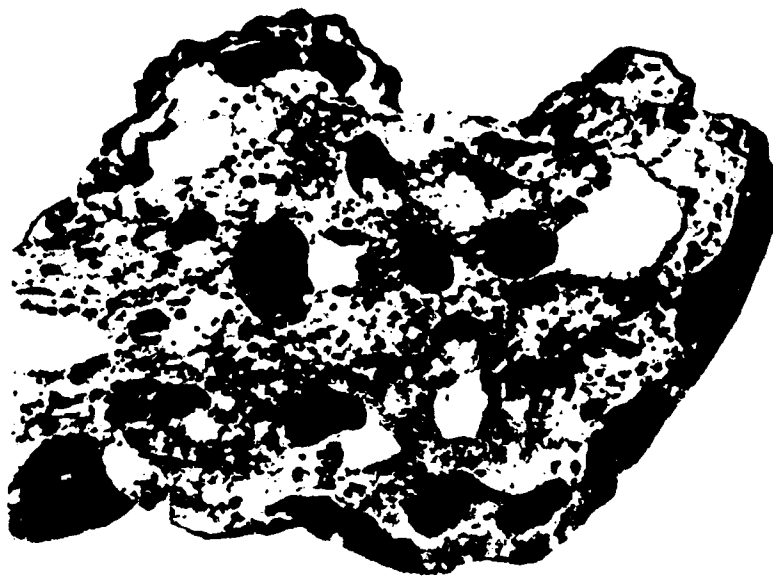
Figure 6. Silica-glass from Wabar (from Spencer (Ref. 11)).

We shall discuss some of these peculiarities briefly below.

1. The Geographical Distribution and Scales of Localization.

The largest field of distribution of tektites is the Australian continent (refer to Figures 1 and 2). Apparently an equally large field is to be found in the region of Indonesia if we consider the scattered nature of the individual islands. This region is adjoined by neighboring fields--Indochina and Southern China and the Philippines--which can be included in a large tektite region or be regarded in the form of individual (perhaps quite small) fields which adjoin each other and merge into one another or are superimposed on each other. These relationships are shown clearly for Australia, Indochina, and even such microregions as Bohemia, Moravia, and the Philippines. In the 1920's all the fields were connected in one diagonal belt, but the discovery of new fields disrupted this pattern and showed that tektites are more or less characteristic for all continents.

However, the dispersion of individual points could scarcely be considered uniform. Although the presence of "empty" spaces in Central and Northern Asia is explained by the lack of study of these territories and other random factors, the colossal concentration of tektites in a single region in Europe undoubtedly indicates the local character of their distribution.

The following figures give an idea of the scale of localization. Tens of thousands of tektites have been found along the Vltava (Moldau) River over an area of 5,000 square km, which means about ten pieces per square kilometer. In some regions in Australia there have been up to 2,000 finds per 500 square km, which means four finds with a total weight of about 8 grams per square kilometer. In Tasmania the gravel beds around Mount Darwin contain up to 50 - 100 grams of silica-glass per square kilometer. Up to 30 fragments with a total weight of more than 100 kg are found per square kilometer of surface in individual accumulations of Libyan glass.

The average weight of individual specimens of tektites varies within a range of 1 - 2 to 10 grams and more. Individual specimens of moldavites, australites, and philippinites weigh several hundreds of grams and some indochinites and libyites several kilograms. Thus, the total mass of finds amounts to not less than several tons, and the "prospected reserves" to tens or hundreds of tons.

2. The Geological Conditions of Sites.

The general conditions of sites in which tektites and silicaglasses are found are very indicative--in youthful gravel and pebble beds, in the soil and on the surface of the ground (in desert areas). Tektites come out of the soil after heavy rains, appearing in drainage ditches and in the beds of temporary streams. Beds of tektite-bearing pebbles and gravel are usually of alluvial origin and cover rocks of any petrographic composition and any age. In Australia and Southeastern

Asia these gravel beds often contain tin and gold. Paragenesis of tektites with tourmaline has been noted (this may be chance) in Moravia, Indonesia, and the Philippines. In case the character of modern processes of geological accumulation is intense, these deposits may be covered by layers of more youthful deposits: limestone (Moravia), clay (Bohemia), peat (Tasmania), etc. The depth of the cover reaches several meters at times. The age of tektite-bearing rock varies from the Middle Tertiary to the Late Quaternary. The tektites of West Africa and Europe are the oldest geologically, and the most youthful are the australites. Thus, the formation of tektites took place in a comparatively short geological interval of time, but not simultaneously.

3. Shapes and Structure.

The following shapes are most typical for tektites: spheres (at times hollow, refer to Figure 4), ellipsoids, pine cone-shaped, drops ("tears"), disks, and buttons, oval plates, boat-shaped, fingers, dumbbells (refer to Figure 3), sickles, and bells. Rounded shapes are most characteristic of moldavites, billitonites, and rizalites; flattened shapes for australites; dumbbells to the same extent for australites and indochinites.

The general peculiarity of sculpturing appears in the presence of furrows and wrinkles which give an impression of rotation and fluidity, small rounded sickle-shaped depressions (nail-marks), at times connected in circles, and the larger ones--the so-called "worm tracks", also tiny open and half-open caverns which give rise to a microslag structure (Figure 8). "Worm tracks" are very characteristic of billitonites and some philippinites. The "wrinkles" on moldavites constitute a special feature which differs from those of other tektites and which caused the first investigators to compare moldavites with the piezoglyptic sculpturing on meteorites. F. Suess (Ref. 1) attempted to reproduce this sculpturing by placing a piece of rosin under a steam jet. It reminds one somewhat of an unopened rose or round gypsum concretions from clay deposits. Billitonites have the coarsest sculpturing, in the form of deep scar-like furrows, both concentric and radial. With their general uniqueness, the "nail-marks", "worm tracks", and "scars" are undoubtedly genetically connected, and often form mutual transitions.

Sculpturing is connected with the general riddle of the origin of tektites, but attempts to unravel the sculpturing picture still lead to diametrically opposite results. Some, such as Suess, Hanus, Baker, Krause, and Walcott see proof of the extraterrestrial origin of tektites in them; others, Stelzner, Berwerth, and Krinov see evidence of terrestrial erosion and corrosion.

The internal structure of tektites corresponds to thoroughly melted glass. M.P. Volarovich and A.A. Leont'yeva were first to direct attention to this peculiarity, pointing out that such thorough melting is the consequence of prolonged high-temperature heating which excludes the possibility of the formation of these bodies in the earth's atmosphere.

Figure 7. Indochinite with the shape of an onion (from
Lacroix (Ref. 50)). One-half natural size.

4. Color and Fundamental Physical Properties.

The majority of typical tektites have a black color (greenish or
brown in thin fragments). A green tone prevails in moldavites, so that
they are called bottlestones with more justification than the others.
Americanites and some tektites from the Philippines differ sharply in
color (violet, brownish-violet, reddish-violet, gray, greenish-yellow).
Tyepical silica-glasses are distinguished by a general shift of the
spectrum from blackish-greens to greenish-yellow tones (clear up to yel-
lowish and almost colorless). The color of impactites varies--different
shades of green, also brown, reddish, yellowish, usually with a general
green background.

Figure 8. Sculpturing on rizalite (by the author).

The values of the indices of refraction (Table 13) depend essentially on the SiO_2 content (also on some other components). Therefore,

modern industrial glasses are distinguished by indices of refraction in a range of 1.48-1.53; in fulgurites it is equal to 1.46.

Spectral and optical studies of tektites in ultraviolet and infrared light (Refs. 86, 131, 132) have indicated the presence of all the basic components in the form of oxides, including iron in both valences, which points toward insufficient reducing conditions at the time of formation. When the Fe_2O_3 content is increased, the maximum of transparency is shifted from the green to the red region of the spectrum and the color of the glass becomes brown instead of yellowish-green. On the whole, the optical density of the glass increases with an increase in the iron content, in the transition from silica-glasses to tektites and, in particular, to australites. The absorption of H_2O and CO_2 at 2,800

Angstrom units is apparently connected with the conditions of formation of the glasses: it is very small in philippinites and bediasites; on the other hand, silica-glasses from the Libyan Desert differ sharply from real tektites in this respect and approach fused quartz and some high-silica industrial glasses.

As compared with ordinary glasses, the linear thermal expansion of tektites is specific (Figure 9) (Ref. 133). Tektites differ in a

Name	Index of Refraction
Australites, silica-glass from Henbury	1.54
Billitonites	1.52
Philippinites, indochinites, Java tektites	1.51
Tektites from West Africa and bediasites	1.50
Moldavites and tektites from Peru	1.49
Tasmanites	1.48
Silica-glass from Wabar	1.47
Libyite and silica-glass from Arizona	1.46

Table 13. Indices of Refraction of Tektites and Silica-Glasses.

like manner in respect to ductility. The data of M. P. Volarovich and A. A. Leont'yeva (Ref. 19) (Figure 10) show that the ductility varies from 1 billion to 200-100 thousand absolute units respectively in an interval from 950-1,400°; this value is 10,000 times larger than in ordinary glasses due to the higher Al_2O_3 content. The departure of tektites

from the restricted region of ductility of erupted rock permits one to draw some far-reaching conclusions.
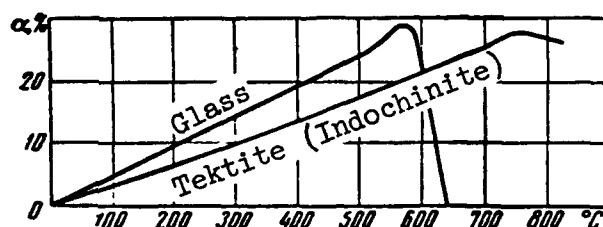
Figure 9. Linear thermal expansion of tektite (indochinite) and glass (according to Chevenard (Ref. 133)).

Of the other physical constants of tektites, one may note the hardness, which is usually within a range of 6-6.5 by the Moh's scale and the specific gravity, which varies from 2.1 to 2.7 (Table 14).

This value is a function of the admixture of oxides of heavy metals in glass. The specific gravity of obsidians is 2.35 to 2.50 and that of fulgurites (from Belgium) is 2.20.

5. The Chemical Composition.
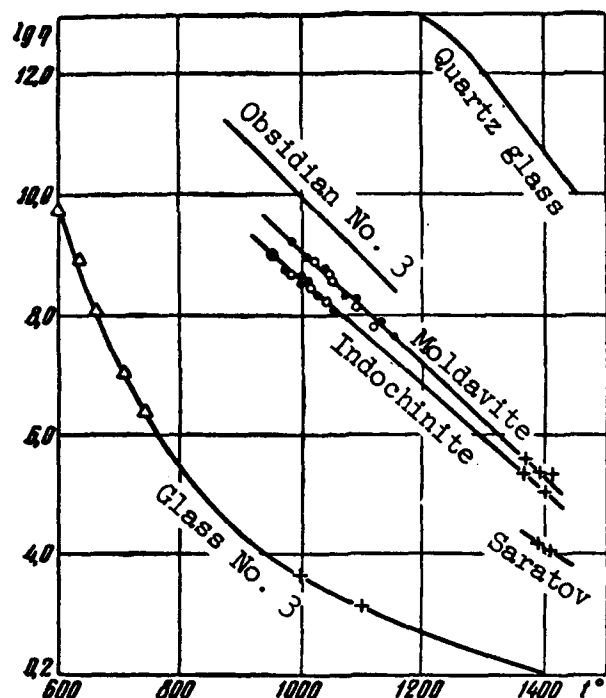
Figure 10. Ductility of tektites, meteorites, artificial glass, and obsidian; symbols mark points obtained by different methods (from the work by M. P. Volarovich and A. A. Leont'yeva (Ref. 19)).

Name	Specific Gravity
Schonites	2.71
Billitonites	2.48
Australites	2.45
Philippinites, indochinites	2.44
Bediasites	2.37
Tektites from Peru	2.35
Moldavites	2.34
Tasmanites and silica-glass from Henbury	2.30
Libyite	2.21
Silica-glass from Arizona and Wabar	2.10

Table 14. The Specific Gravity of Tektites and Silica-glasses.

The data given in Tables 2 - 12 permit one to establish the general limits of the basic composition of tektites and silica-glasses.

Of the three groups of tektites which have been most carefully

analyzed, the australites show the greatest dispersion in composition, and the indochinites the least. Moldavites differ from australites by increased amounts of SiO_2, Al_2O_3, and K_2O with decreased amounts of FeO,

CaO, MgO, and Na_2O. Australites differ from indochinites and moldavites

in their high Fe_2O_3 content. On the whole, the silica-glasses are more

acid than tektites; the impactite from Henbury is an exception with 68.88 percent SiO_2 due to the very high iron content. Modern industrial

glasses contain 54-81 percent SiO_2, up to 15 percent Al_2O_3 + Fe_2O_3, up

to 16 percent CaO, up to 5 percent MgO, up to 17 percent Na_2O and 13

percent K_2O. All of them are distinguished by a considerable alkali

content. Tektites differ from volcanic glasses by the ratio of components, as was noted by a number of investigators (Refs. 51, 99, 119).

Oxides	Content, Percent Weight	Number of Determinations
SiO_2	47.54-98.44	102
TiO_2	Traces-3.64	99
Al_2O_3	0.49-20.54	116
Fe_2O_3	0.00-8.46	65
FeO	0.13-11.51	127
MnO	Traces-1.25	96
CaO	0.00-8.56	116
MgO	Traces-7.90	116
Na_2O	0.01-3.96	113
K_2O	0.00-4.67	95

Table 15. Limits of Chemical Composition of Tektites and Silica-glasses.

A relatively high nickel concentration is very typical of tektites (but is not obligatory). Tektites and silica-glasses are given in decreasing order of the nickel content in Table 16.

Specimen Studied	Content, Percent
Silica-glass from Wabar	Up to 0.35
Silica-glass from Henbury	0.28
Australites	Up to 0.06
Billitonites	0.03-0.044
Tasmanites	0.04
Libyite	Traces-0.032
Indochinites	0.001-0.028
Silica-glass from Aouelloul	0.019-0.025
Moldavites	0.001-0.003
Americanites	Less than 0.001
Bediasites	Not Found

Table 16. The Nickel Content in Tektites and Silica-glasses.

Recalling that the average content of this element in sedimentary rock is $9.5 \cdot 10^{-3}$ percent and in volcanic rock $8 \cdot 10^{-4}$ percent (acid) to $1.2 \cdot 10^{-1}$ (ultrabasic) (Ref. 133), one can state that tektites do not correspond at all to sedimentary rock in respect to nickel content, but coincide with neutral and basic rock (with their ultraacid macro-composition!). G. G. Vorob'yev (Refs. 20, 22) showed that the Ni : V and Ni: Co ratios in moldavites approach basic and neutral rock while the ratios in indochinites approach those of ultrabasic rocks and even meteorites. Thus, if we apply terrestrial conditions, tektites can be called hybrid rock with an anomalous microelementary composition—which provides evidence of superposition of the basic (or meteoritic) phase on the acid phase. This process is displayed more strongly in indochinites and more weakly in moldavites.

Uranium is one of the other microelements which is of interest in tektites (Table 17).

Sedimentary rocks contain $3.2 \cdot 10^{-4}$ percent uranium; when passing from acid to ultrabasic rocks, the uranium content drops from $3.5 \cdot 10^{-4}$ to $3 \cdot 10^{-6}$ percent (Ref. 133). With the exception of americanites, all tektites have a comparatively narrow range of uranium content from $1 - 3 \cdot 10^{-4}$ percent, which means they approach neutral rocks.

Place of Finds	10^{-4} Percent
Peru	18.0
Thailand	3.0
Philippines	1.7-2.7
Australia	1.6-2.4
Indochina	1.1-2.5
Texas	1.1-2.4
Bohemia	1.5-1.6
Java	1.5
Billiton	1.4
Libya	1.1
West Africa	0.91

Table 17. Uranium in Tektites (According to Friedman (Ref. 60)).

However, it seems that the amount of water distinguishes tektites most clearly from terrestrial rocks. Friedman gives the general limits
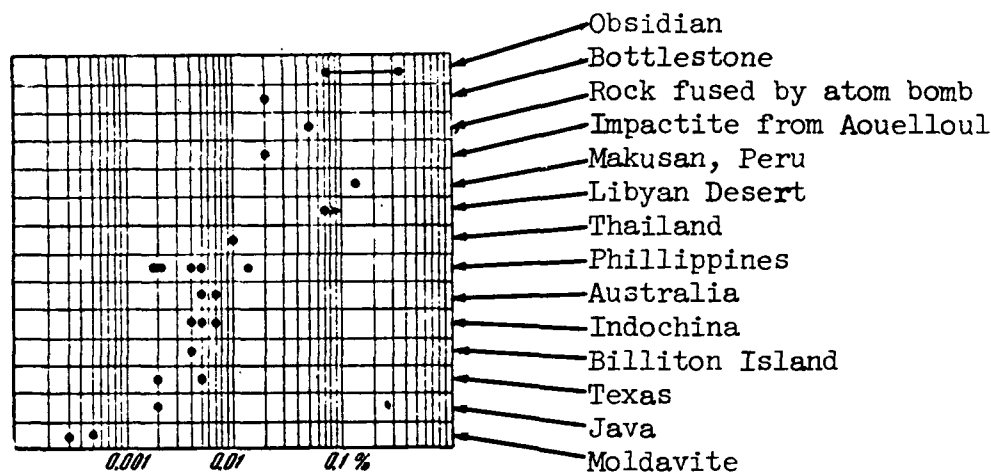
Figure 11. Water content in tektites, silica-glasses, and volcanic glasses (according to Friedman (Ref. 60)).

of the H_2O content as varying from 0.23 percent (Peru) to 0.0003 percent (Bohemia), this value varying from 0.01 to 0.001 for the majority of tektites. This separates them sharply from ordinary obsidians (Figure 11).

A great deal more attention must be devoted to studying the composition of tektites since the interpretations of the information

obtained still yield conflicting results.

6. Isotopic Composition and Absolute Age.

Systematic isotopic studies should yield more definite results. At present we have available somewhat dispersed but very promising data, especially due to the most recent works of Ehman and Kohman.

Tektite	K (g/g)	Ar (ml/g)	K^{40} (g/g)	Ar (g/g) Age(Years)
Rizalites	0.0171	$8.0 \cdot 10^{-7}$	$2.0 \cdot 10^{-6}$	$<14.3 \cdot 10^{-10} < 1.2 \cdot 10^{7}$
Indochinites	0.0228	$3.8 \cdot 10^{-7}$	$2.7 \cdot 10^{-6}$	$< 6.9 \cdot 10^{-10} < 4.6 \cdot 10^{6}$
Moldavites	0.0314	$4.2 \cdot 10^{-7}$	$3.8 \cdot 10^{-6}$	$< 7.5 \cdot 10^{-4} < .1 \cdot 10^{6}$

Table 18. The Absolute Potassium-Argon Age of Tektites.
(According to E. K. Gerling and M. L. Yashchenko)

In 1951 - 1954 Suess (Refs. 57, 136) and E. K. Gerling and others (Refs. 18, 137) reported on the results of determination of the potassium-argon age of tektites. The age of rizalites, indochinites, and moldavites as given by E. K. Gerling and M. L. Yashchenko, is given in Table 18.

Tektites	K, %	Rb, 10^{-4} %	Sr, 10^{-4} %	$Sr^{84}:Sr^{88}$	$Sr^{86}:Sr^{88}$	$Sr^{87}:Sr^{86}$
Indochinites	2.2	126	117	0.0068	0.1199	0.712
" "	2.1	110	111	0.0068	0.1199	0.712
" "	---	110	120	0.0069	0.1185	0.715
Australite	2.1	111	141	0.0066	0.1185	0.695
" "	2.1	110	{284 298	0.0069	0.1200	0.709
Philippinites	2.4	141	150	0.0067	0.1192	0.712
" "	---	{104 112	162	0.0072	0.1191	0.712
Moldavite	2.7	130	136	- - -	- - -	- - -

Table 19. The Absolute Rubidium-Strontium Age of Tektites.
(According to Pinson and others)

According to Suess, the age of tektites is less than $73 \cdot 10^6$ years. The practical absence of argon with a large potassium content permits one to doubt the cosmic origin of tektites.

At the International Conference on Tektites in 1957 (Washington, D. C.), a group of investigators headed by Pinson (Ref. 85) reported on the results of determining the age of tektites by the rubidium-strontium method. (Table 19).

The lack of an increment of radiogenic Sr^{87} indicates a very youthful age of tektites, and thus is in accordance with data obtained from the potassium-argon method. According to Pinson, however, the very constant content of this isotope for such large areas permits one to doubt the possibility of terrestrial origin of tektites.

A third--the lead method for determining age--was applied by I. Ye. Starik and M. M. Shats (Ref. 104) and yielded entirely different results (Table 20).

Pb, 10^{-7} g/g	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}	U, 10^{-6} g/g	Pb^{206} : U^{238}	Pb^{207} : U^{235}	Pb^{207} : Pb^{206}	Age Yrs.
76.0	1	28.91	17.53	41.67	1.2-$2.0 \cdot 10^6$	4.7	42	37	$\sim 4 \cdot 10^9$

Table 20. The Absolute Age of Indochinites by the Lead Method. (According to I. Ye. Starik and M. M. Shats).

Tilton (Ref. 87) also determined the isotopic composition of lead for other tektites (Table 21).

Name	Pb^{206} : Pb^{204}	Pb^{206} : Pb^{207}	Pb^{206} : Pb^{208}
Australite	18.81	1.206	0.486
Moldavite	18.55	1.185	0.483
Philippinite	18.83	1.199	0.482
Libyite	19.11	1.213	0.488

Table 21. The Isotopic Composition of Lead in Tektites (According to Tilton)

These figures differ from those obtained by I. Ye. Starik and
M. M. Shats and permitted Tilton to draw a conclusion of the terrestrial
origin of tektites by considering the usual isotopic composition of
lead and the usual U : Th ratio in australite (1 : 5.28).

Friedman determined the amount of deuterium in tektites (Refs.
60, 139). The values he obtained vary somewhat: from 0.0127 mol. per-
cent (Peru) to 0.0166 mol. percent (Thailand). The average value is
noticeably high as compared with rhyolitic glasses.

There is no doubt that the most interesting isotopic data were
obtained by Ehman and Kohman (Refs. 140, 141). They showed that tek-
tites contain the radioactive isotopes Al^{26} and Be^{10} caused by cosmic
rays, in quantities exceptional for the earth's surface and quite usual
for meteorites (Table 22). This implies that tektites (and Libyan
glass) are glassy meteorites and have been in terrestrial space for at
least one million years. Their approximate "terrestrial age" was estab-
lished in comparison with meteorites (chondrites):

Libyite	3.5 million years
Moldavites	3 million years
Bediasites	>1.2 million years
Australites	<0.5 million years

These data agree to some extent with the geological conditions in
which the tektites were found.

Name	Al^{26}	Be^{10}
Stone meteorites	$6.3 \cdot 10^{-2}$; $5.4 \cdot 10^{-2}$	$5.1 \cdot 10^{-3}$; $1.62 \cdot 10^{3}$
Iron meteorites	$5.5 \cdot 10^{-3}$; $< 6 \cdot 10^{-4}$	$7 \cdot 10^{-4}$; $< 4.9 \cdot 10^{-4}$
Australite	$4 \cdot 10^{-2}$	$3 \cdot 10^{-3}$
Bediasite	$< 2.2 \cdot 10^{-2}$	$5.2 \cdot 10^{-3}$
Moldavite	$< 3.2 \cdot 10^{-2}$	$1.2 \cdot 10^{-3}$
Libyite	$3 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$

Table 22. Relative Radioactivity of Meteorites and Tektites
Disintegrations/Min-Gram (after Ehman and Kohman).

7. Gaseous and Solid Inclusions.

The problem of inclusions occupies a special position in the problem of tektites and requires painstaking study. On the whole, inclusions are not very characteristic for tektites. Professor Makowsky (Refs. 28-30) was first to direct attention to the absence from these bodies of crystallized minerals, which are quite usual in volcanic glasses. M. P. Volarovich and A. A. Leont'yeva (Ref. 19) believe that a temperature above 2,000° is required to produce specially pure glass without gas bubbles, which would place the process of tektite formation under exceptional conditions. Nevertheless, gas bubbles are present in the majority of tektites. They are quite numerous in individual territorial groups, in individual specimens, and in individual parts while they form dull white zones in some silica-glasses. According to the data obtained by a number of investigators (Refs. 51, 57, and 61), the composition of gaseous inclusions varies within the ranges given in Table 23.

Components	Content, Percent of Volume	Components	Content, Percent of Volume
CO_2	6-46	CH_4	Up to 2
CO	24-92	O_2	Up to 1
H_2	1.5-41	N_2	Up to traces
H_2O	Up to 15	SO_2	Up to 0.2

Table 23. Limits of the Chemical Composition of Gaseous Inclusions in Tektites

Suess (Ref. 57) emphasized a definite genetic connection between tektites and the composition of the gaseous inclusions which are generally specific and vary within a definite interval.

Mineral inclusions in the form of crystallized glass are encountered only in americanites and some silica-glasses. No detailed descriptions of them are available.

Finally, magnetic iron spherules constitute a special type of inclusion which was discovered in large quantities for the first time in impactites (Ref. 10). According to data from G. G. Vorob'yev (Ref. 21), hollow magnetite spherules, partially or wholly replaced by limonite, are concentrated on the surfaces of some rizalites. The presence of

0.087 percent nickel was established for one of these spherules. Their diameter is usually 1 - 2 mm and on rare occasions drops to several tenths of a millimeter. When they come to the surface they spread out over a plane, this fact being apparently of genetic significance. Spherules of unknown composition and considerably smaller dimensions (from tenths of a micron to > 10 microns) have been discovered in indochinites (Ref. 20) and in moldavites (Ref. 22).

These facts can be compared with finds of numerous spherules of magnetite with different nickel content and different dimensions (from 3 - 6 to 60 microns) in the bottom deposits of oceans (Ref. 142) and on the surface of continents in the composition of atmospheric dust (Ref. 143). It is assumed that they were formed by being blown from the surfaces of meteorites during their flight through the atmosphere.

8. The Folklore of Tektites

It is necessary to say a few words on the fantastic names and legends connected with the question of the origin of tektites. The natives of Southeastern Asia and Australia have known tektites for hundreds and thousands of years. Therefore, the probability of noting their fall as glass meteorites over such a long period is quite well-founded. One is struck by the complete uniformity of names over the territories of Indonesia, Indochina, Southern China, and the Philippines (moon stones or balls, sun stones, thunder stones or feces, lightning stones, star feces, etc.). Taking the probability of historic fiction and exaggeration into account, these expressive names should be considered in the general balance of theories of the origin of tektites.

Questions of Origin

In the historic sense, the evolution of theories of the origin of tektites began with a "volcanic" stage; after a time, the probability of artificial origin came under consideration; then a prolonged period of "extraterrestrial" theories set in, now subject to doubt among a number of investigators who assume the probability of terrestrial (but exceptional) origin. The latter two developments continue to be propagated.

The idea of cosmic (extraterrestrial) origin was advanced for the first time in 1898 for moldavites by Rzehak (Ref. 36), for australites by Walcott (Ref. 6), and for billitonites by Krause (Refs. 92, 93). Later Suess (Ref. 1) developed this into a quite well-founded theory, regarding the surface structure of tektites as evidence of their flight through the atmosphere. This theory acquired a large number of adherents and served as an impetus for the development of new theories in this direction. Michel (Ref. 144) believes that tektites were formed by differentiation of meteoritic material in the earth's atmosphere under the action of high temperatures. The well-known investigator Paneth

(Ref. 144) shared this opinion, assuming the possibility of the process of remelting in the perihelion zone. At present the meteorite theory (Refs. 134, 147-149) regards the origin of tektites in connection with the destruction of a planet (or several planets) similar to the earth and located between Mars and Jupiter due to a collision with another similar planet or with one of Jupiter's satellites about 100 million years ago. Planetary fragments provided the origin of meteorites and fragments of the acid surface layer to tektites after prolonged heating

to 1,500 to 2,500°. Because of their fragility, tektites were shattered in the earth's atmosphere and scattered over large areas. The structure of tektites provides evidence that they are parts of one or several large bodies. Beading on their surfaces, the shapes of rotation and sculpturing are of atmospheric origin, according to a number of authors (Refs. 80, 81, 134).

The so-called "lunar theories" developed side by side with the meteoritic theories and pictured tektites as products ejected by volcanoes on the moon (Verbeek and others (Refs. 90, 91), or as fragments of rock from the moon's surface torn loose by impacts with huge meteorites (O'Keefe and others (Refs. 150 and 151)). In the last case the fragments should have fallen on equatorial regions of the earth.

In most recent times, Kohman and Ehman (Ref. 140) have made the assumption, based on isotopic investigations which we have mentioned previously, that tektites are fragments of a swarm of glassy objects which entered the solar system from outside (otherwise the swarm would have been dispersed by protracted movement through the solar system). This theory should acquire further development since it is based on very interesting experimental material.

The theory of meteoritic craters advanced by Spencer (Refs. 4, 5, 124-127, 130), which explains the formation of tektites in collisions of meteorites with the earth's surface, is close to the purely cosmic theories. Molten silicate rock sprayed out at this time into the air hardened to acquire a characteristic structure. In recent times the Urey hypothesis (Refs. 152-154), which assumes a collision between the earth and the nucleus of a comet, has gained recognition along with the theory; the explosion resulted in the melting of sedimentary rocks and their scattering over a large area.

Despite their apparent soundness, the cosmic theories suffer from a number of shortcomings. This is evidenced by age data obtained by the argon method (Refs. 18, 137), the isotopic composition of lead content (Ref. 87) the similarity with the composition of sedimentary rock (Refs. 17, 152), and the probable erosion origin of structure (Refs. 129, 130).

The formation of tektites in the atmosphere should be hampered by

the factors of insufficient amount of oxygen for complete oxidation and great ductility, which would require prolonged high temperatures (Ref. 19). In criticizing the lunar hypotheses, Barnes (Refs. 149, 151), Kopal (Ref. 151), Urey (Refs. 151,155), and Kolman (Ref. 140) noted that the distribution of tektites over the earth's surface in the form of separate groups cannot be explained by a mechanism of lunar origin; the dispersion of initial velocities after collision with a meteorite should lead to too wide a scattering of the fragments to permit their reaching the earth; the assumption of lunar material being ejected in the form of a cone of limited dimensions is not probable due to different velocities and angles of collisions of meteorites. If tektites are lunar material, then the processes on the moon which formed acid rocks would be different from corresponding processes on the earth, which is very difficult to believe; the presence of radioactive isotopes of cosmic origin in tektites excludes the possibility of their formation within the bounds of the earth or of its satellite. The great difficulties in explaining the mechanism of the formation of the surface structure constitute the weak aspect of the theory of Spencer and Urey.

Terrestrial theories are more weakly developed. They are based essentially on the principle of exclusion in which some of the above-mentioned reasoning on the cosmic nature of tektites is subjected to doubt. In addition to the obsolete "volcanic" theories (Refs. 3, 8, 24, 69, 70-72) and the theory of artificial origin (Refs. 24, 28-30, 35), which are no longer defended by anybody, one may mention the "pneumato-genic" (Ref. 110) and the "carbon" (Ref. 24) theories as historic fact. Barnes (Ref. 119) regards tektites as fused sedimentary (tasmanites, bediasites, moldavites) and igneous (indochinites, billitonites, australites) rocks. At the same time, Friedman (Ref. 60) emphasized that tektites could be formed under terrestrial conditions only as a result of exceptional catastrophic processes. Explosions of atom bombs in which there are silica-glasses similar to the impactites of meteorite craters can serve as examples of such processes.

The criticism of terrestrial theories is based essentially on two facts.

1. One's attention is directed (Refs. 19 and 152) to the fact that the melting point and the ductility of tektites require special

high-temperature conditions (over 2,000°) for their formation--conditions which correspond to the discharge of atmospheric electricity (in this case, however, bodies are formed which have nothing in common with tektites).

2. Determinations of age by the lead method (Ref. 104), the peculiarities of the isotopic composition of lead (Ref. 104) and strontium (Ref. 85) content, the presence of radiogenic isotopes of cosmic origin

(Refs. 140, 141) also permit one to doubt the probability of the terrestrial origin of tektites.

Conclusions

Tn his last work Barnes (Ref. 149) undertook to summarize the results of many years of discussions on the origin of tektites. He summarized all the data obtained up to the present in a table which we shall present here.

Origin	Terrestrial						Lunar		Extraterrestrial	
			Due to Collisions							
	Volcanic	Lightning	Meteorites	Asteroids	Comets	Atom Bomb Explosions	Volcanic	Collision	Collisions between Asteroids	Destruction of a Planet Similar to the Earth
Two periods of fusion	-	-	-	?	?	-	-?	+	+	+
Presence of lechaterierite	-	+	+	+	+	+	-	-	-	+
Striated surface	-	?	+	+	+	+	-	+	+	+
Chemical composition	-	+	-?	-?	+	+	-	-	-	+
Shapes	?	-	+	+	+	-	?	+	+	+
Dimensions	+	-	+	+	+	-	+	+	+?	+
Distribution	-	-	-	?	?	-				
Age	-	-	+	+	+	-	+	+	+	+

Table 24. A Comparison of the Facts With Existing Theories
On the Origin of Tektites (According to Barnes)

It has been shown on the basis of the most important genetic properties (chemical composition, the presence of lechatelierite, the existence of two periods of fusion undergone by tektites--with australites as an example--the fluidal structure, their shapes and dimensions, their distribution on the earth's surface and age) that the facts which confirm and deny the terrestrial origin of tektites are roughly equal while the facts which assume extraterrestrial origin prevail heavily over the facts which deny it.

Thus, at our present level of knowledge, the cosmic or semicosmic (impact) origin of tektites seems more probable--the result of destruction of planets similar to the earth (the meteorite theory), collisions between the earth and comets or asteroids, or collisions between meteorites and the surface of the earth and the moon. Two purely terrestrial variants--ejection from volcanoes and lightning--should be rejected as the majority of the facts does not agree with those theories. The overwhelming majority of the critics of cosmic theories arrive at a terrestrial variant by exclusion without being able to advance a single more or less well-founded theory. In order to develop such a theory it will be necessary to unify the facts of distribution over large areas and the superimposed distribution of tektites, their presence on the surface of the earth or in deposits with original shapes and sculpturing, the peculiarities of their chemical composition, and the possibilities of fusion with the formation of lechatelierite. This process undoubtedly should be of a local nature and closely connected with existing petrogenetic processes. No detailed descriptions have been given as yet by geologists or by geochemists, and therefore the cosmic theories cannot be refuted as a whole at this stage.

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IV. AN X-RAY STUDY OF THE COMPOSITION OF CERTAIN METEORITES *

by N. N. Stulov

Russian Text Pages 63-85

This work was undertaken jointly with Professor V. I. Mikheyev. In the first stage of the work we intended to solve two problems with an x-ray method: a) to determine the mineral composition of certain meteorites from the collection in the Mining Museum and b) to investigate specially selected mineral fractions from individual meteorites sent by L. G. Kvasha from the Committee on Meteorites of the Academy of Sciences, USSR to the laboratory.

Solution of the second problem was to improve the accuracy of the identification of minerals from meteorites and obtain standard x-ray diffraction patterns for minerals from them. The last circumstance made it possible to undertake to establish standards for determination of the minerals in meteorites.

The last stage of our work was intended to establish such a standard of determination. The premature death of V. I. Mikheyev made it impossible to complete the work in accordance with our plans.

This article contains the results obtained from processing the x-ray diffraction patterns taken jointly with V. I. Mikheyev, part of which were interpreted jointly with him. Thus, a summary of the factual material obtained is the objective of this article. (Laboratory Assistant A. I. Kalinin, who took the x-ray photographs of specimens of the meteorites and measured the majority of them, participated in this work.)

The author of this article made an x-ray study of the mineral composition of a number of iron meteorites, also some carbonaceous chondrites. A list is given below of the meteorites or individual samples of minerals from them which were investigated.

The Method of Study

Chips obtained by careful drilling of meteorites with a hard drill or with a file were taken to serve as material for the study of the iron meteorites in the Mining Museum. The samples obtained from the Committee on Meteorites from L. G. Kvasha were already finely powdered material. In some cases these samples were ground in an agate mortar in order to grind them uniformly to 0.01-0.001 mm.

A column of the powder to be studied was pressed into a glass capillary tube with a diameter of 0.8 mm. Two pictures were made of each

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*Commas in tables and graphs represent decimal points.

Number of Sample	Meteorite	Description of Samples	Remarks
1	Sikhote-Alin'	Kamacite and perhaps taenite	All three samples were taken from different sections of one
2	"	Same	band of kamacite from individ-
3	"	Same	ual specimen No 2052.
4	"	Same	From two sections of a band
5	"	Same	from another sample. Individ- ual specimen No 1462.
12	"	Same	From bands of specimen No 1601/ IV.
8	"	Chromite(?)	Residue after dissolving the total sample of troilite.
6	"	Troilite (total sample) with inclusions of daubreelite (?) or chromite (?), or both, and perhaps carbona- ceous material.	
7	"	Troilite	One grain from specimen No 2052.
9	"	Schreibersite	From specimen No 2052.
10	"	Residue from dissolving nickeliferous iron. Probably rabdite and perhaps carbonaceous material.	
11	"	Same, but larger frac- tion	
103	Bobaybo	Heavily contaminate mat- erial collected from different parts of the meteorite	
6/n	"	Same	

TABLE I. IRON METEORITES

A. SAMPLES FROM THE COMMITTEE ON METEORITES, USSR ACADEMY OF SCIENCES
(Obtained from L. G. Kavasha).

sample--one with the pure material, the other with a mixture of the smaple with rock salt. The rock salt was used as a standard substance for introduction of a correction for absorption of the preparation and other experimental errors.

Number of Meteorite	Catalo Number	Meteorite and Its Characteristics	Remarks
18	36	Coahuila (Fort Duncan), Mexico. Known since 1837. Iron metesrite with troilite and rabdite inclusions. Weight 174 grams. Hexahedrite.	No figures were discovered after etching in a five percent solution of mitric acid in alcohol.
23	61	Hex River Mountains. South Africa. Found in 1882. Hexahedrite. Plate with a weight of 29.8 grams.	
13	34	Chesterville, North America. Found prior to 1849. Ataxite, poor in nickel. Plate with a weight of 14.63 grams.	
48	126	Sao Juliao de Moreira, Portugal. Found in 1883. Octahedrite--deep structure. Plate with a weight of 80 grams.	Coarse (width of 3-5 mm) white and gray section and strips observed after etching. Filings were taken from both sections for x-ray analysis.
11	28	Carlton, United States. Found in 1887. Octahedrite. Plate with weight of 114 grams.	Widmanstaetten figures were clearly displayed after etching.
53	140	Tazewell, United States. Found in 1853. Octahedrite. Weight 34.2 grams.	Widmanstaetten figures clearly displayed on specimen. Had a fused crust which was also investigated.

* The data on meteorites were checked with the Catalog of the Meteorites of the World, Prior and Hay, 1953.

B. SAMPLES FROM THE COLLECTION OF THE MINING MUSEUM (Ref. 7)*

The distances between the centers of the lines of symmetry of the pictures were measured with a half-millimeter scale, the arithmetical average being taken of three measurements for each pair of lines. The relative intensities of reflection were evaluated visually by blackening of the lines of Debye powder patterns. The brightest line was given a mark of 10 and the weakest line, scarcely discerned by the eye was given a mark of 1.

Meteorite	Place Sample Was Taken
Staroye Boriskino ⎱ Cold Bokkeveld ⎰ Orgueil (France)	Committee on Meteorites, Academy of Sciences, USSR Mining Museum

TABLE II. CARBONACEOUS CHONDRITES

In order to improve the accuracy of computation of the parameters of the mesh and in order to catch the fluctuations in these parameters in different samples of nickeliferous iron (kamacite and taenite) the pictures were taken in cameras with a diameter of 143 mm with the purpose of splitting the lines in the x-ray pattern from α_1 radiation and

α_2 radiation. The pictures were taken with a Hadding ion acceleration tube with an iron anticathode.

The following values were taken in calculating the wavelength:

$$\lambda_{K_{\alpha 1}} = 1.936012 \text{ kX}; \qquad \lambda_{K_{\alpha 2}} = 1.932076 \text{ kX};$$

$$\lambda_{K_{\beta}} = 1.753013 \text{ kX}.$$

In addition, the method of roentgenometric investigation was modified in the following manner:

a) The photographic film in the camera was placed in reverse position, that is, so that the ends of the film were not positioned toward the entry diaphragm, but in the opposite direction. Thus, the lines obtained with large glancing angles were arranged in the center of the picture. This permitted more accurate determination of the values of inter-plane distances; b) glancing angles were determined with accuracy to one-tenth of a minute; c) inter-plane distances were computed for all lines by taking logarithms by the Bragg-Wolf formula; d) a considerable quantity (up to 60 percent) of rock salt was mixed with the sample to be studied in order to introduce corrections for more intense lines. Exposure time was 8 ma x 4.5 hours.

X-ray photographs of all the remaining samples were taken in cameras with a diameter of 68 mm with iron radiation from the x-ray tube ($\lambda_{K\alpha} = 1.934$ kX; $\lambda_{K\beta} = 1.753$ kX). In this case the exposure was

8 ma x 2 hours and in some cases up to 3.5 hours.

I. Iron Meteorites

Kamacite and Taenite. As is well known, iron meteorites consist of nickeliferous iron with insignificant admixtures of other components. Two phases exist in nickeliferous iron. Kamacite, the phase which is poor in nickel (up to 7 percent), has an α-Fe type of structure, that is, a body-centered cubic crystal structure. The second phase is taenite, which is rich in nickel (from 24 percent and higher) and has a close-packed cubic structure (face-centered cubic crystal lattice).

Iron and nickel form a continuous series of solid solutions at a temperature above 870°. The above-mentioned phases of nickeliferous iron are formed during cooling as a result of decomposition of such solid solutions. In spite of the apparent simplicity of the iron-nickel system, nobody has succeeded yet in establishing the actual positions of the boundaries between the phases.

Bradley, Jay, and Taylor (Ref. 13) have studied changes in the parameters of the unit cell for iron-nickel alloys. They determined the parameters of the cell for 35 different alloys. They constructed a diagram on the basis of the data they obtained (Figure 1). According to this diagram, the parameters of the lattices of alloys that are poor in nickel (the kamacite phase) increase with addition of nickel. The increase in the parameters of the lattice is very insignificant and is characterized by thousandths of kX. This increase in the parameters is observed in passing from pure iron to alloys with a content of 5.7 at. percent of nickel. With a further increase in nickel one observes a two-phase region where there are alloys with body-centered and face-centered cubic crystal structure. Debye powder patterns of alloys from this two-phase region have diffused lines, the width of the lines increasing with an increase in the nickel content. This indicates a strong dispersion of the material under study and its amorphous state in some cases. It was possible to determine the parameters of a body-centered cubic structure in two alloys from the two-phase region while it was impossible to determine the parameters of the face-centered cubic structure. The parameter of the unit cell in all three alloys turned out to be 2.8635 kX, even though their nickel content was different. This value of the parameter corresponds to an alloy with 4.4 at. percent nickel for the one-phase curve. Thus, the boundary of the phase for two-phase alloys should have been passed with a content of 4.4 at. percent of nickel. On the other hand, no indications of alloys with a face-centered structure were noted in the alloy with a content of 5.7 at. (atom) percent of nickel.

The right-hand side of the diagram shows the relationship of the

parameters of a face-centered cell for alloys rich in nickel. As may be seen from the diagram, the parameters of the unit cell in this region grow from 3.5168 kX for pure nickel to a maximum value of 3.5878 kX noted in an alloy with 38 at. percent of nickel. The diagram also implies that the variation in the parameters of a unit cell in alloys in the interval from 50 to 100 percent nickel content is not linear. The diagram also shows a straight line between these two points. The observed values drop below this line.
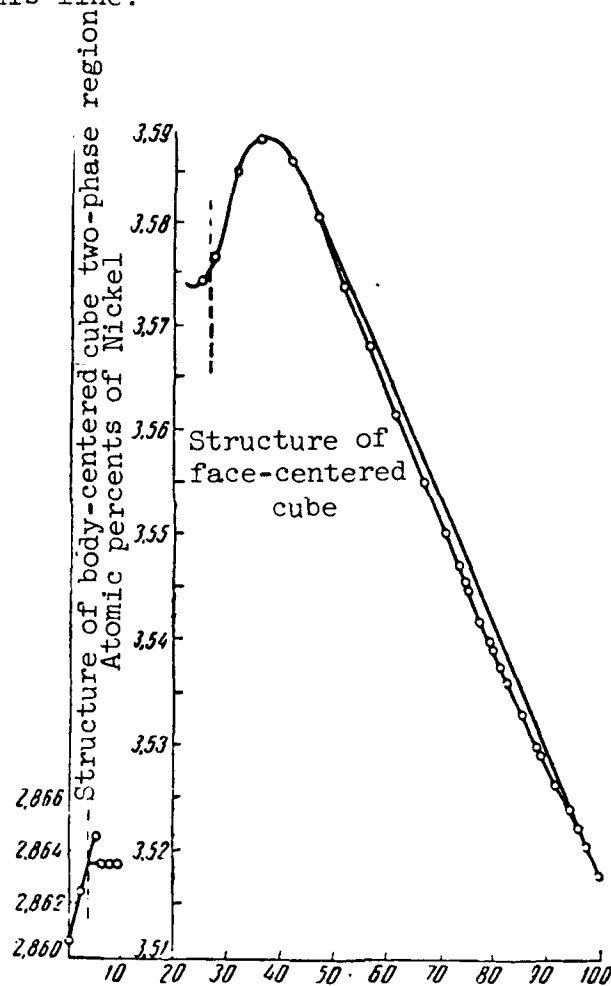
Figure 1. The parameters of kamacite and taenite as a function of the percent of nickel content (according to Bradley, Jay and Taylor).

It should be noted that the parameters of a unit cell of alloys quenched at 700, 800, and 900° turned out to be different from the values observed in experiments with slow cooling. As a rule, the unit cell parameters had large values.

After studying some isomorphic series, V. I. Mikheyev (Ref. 9)

came to the conclusion that changes in the parameters of the lattice in such series were linear and depended on the average radius of the cation. In particular, he suggested a formula for the dependence of the lattice of kamacite on its nickel content, namely: a = 2.86124 + 0.00041 x where x is the atom percent of nickel. By solving the inverse problem, one may determine the nickel content by the lattice parameter. A graphically found law is presented in Figure 2. In deriving this relationship V. I. Mikheyev made use of data available in the literature (Ref. 14).

In determining the percentage content of nickel in kamacites by their lattice parameters with the aid of the diagrams presented in Figures 1 and 2, the results obtained are not identical, particularly along the edges of the graphs.
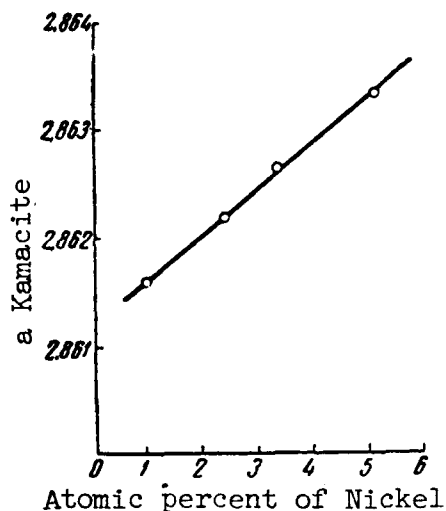
Figure 2. Variation in the side of the kamacite unit cell as a function of nickel content (according to V. I. Mikheyev).

The foregoing implies that the relationship between the dimensions of the unit cell and the constituents of iron nickel alloys is complicated and not completely known as yet. Before making a study of nickeliferous iron in meteorites by the reverse picture method in large diameter cameras, we took x-ray pictures of three samples of pure iron and determined the parameters of their unit cells, which turned out as follows: a) a soft iron wire, a = 2.8607 ± 0.0002 kX; b) filings from critchtonite iron, a = 2.8607 ± 0.0003 kX; chemically pure iron powder obtained by reducing it with hydrogen sulfide, a = 2.8601 ± 0.0005 kX.

The data presented here imply that we obtained almost identical dimensions for the edges of the unit cell for two samples while the size of the cell turned out to be a bit smaller for the third sample. Nevertheless, it must be recognized that the data obtained are in agreement

hkl	Sample 1			Sample 2			Sample 3			Sample 4			Sample 5			Sample 12			hkl of the super-structure
	I	d_α/n	d_β/n	I	d_α/n	d_β/n	I	d_α/n	d_β/n	I	d_α/n	d_β/n	I	d_α/n	d_β/n	I	d_α/n	d_β/n	
—	—	—	—	—	—	-	1	(3,1851)	2,8870	—	—	—	1	(3,1799)	2,8823	—	—	—	200β
—	—	—	—	1	2,8832	2,6133	3	2,8840	2,6140	1	2,8840	2,6140	3	2,8806	2,6110	—	—	—	200
110β	5	(2,2353)	2,0261	5	(2,2348)	2,0256	5	(2,2348)	2,0256	6	(2,2348)	2,0256	5	(2,2348)	2,0256	3	(2,2353)	2,0261	—
110 α₁,α₂	10	2,0256	1,8360	10	2,0251	1,8356	10	2,0277	1,8380	10	2,0260	1,8364	10	2,0247	1,8352	9	2,0273	1,8375	—
—	1	1,7576	1,5930	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
200β	1p	(1,5819)	1,4338	1p*	(1,5824)	1,4310	1	1,5798	1,4310	1	(1,5790)	1,4312	1	(1,5753)	1,4296	—	—	—	—
200 α₁,α₂	7p	1,4339	1,2997	4p	1,4332	1,2991	3	1,4328	1,2987	6ш**	1,4328	1,2987	7ш	1,4324	1,2983	3ш	1,4315	1,2975	—
—	—	—	—	—	—	—	3	1,3639	1,2362	—	—	—	—	—	—	—	—	—	411; 330
211 α₁,α₂	9	1,1700	1,0605	9p	1,1694	1,0600	9	1,1697	1,0602	9ш	1,1698	1,0603	9	1,170	1,0605	8ш	1,1693	1,0598	—
220β	1	(1,1184)	1,0137	1	(1,1157)	1,0113	1p	(1,1161)	1,0117	1	1,1172	1,0126	—	—	—	—	—	—	—
—	1	1,0993	0,9964	—	—	—	1p	1,0956	0,9931	1	1,0655	0,9657	—	—	—	—	—	—	511; 333
—	1ш	1,0624	0,9630	—	—	—	—	—	—										520; 432
220α₂	8	{1,0366	0,9193	6	{1,0129	—	6	{1,0130	—	7	{1,0136	0,9197	7	{1,0123	0,9202	4	{1,0131	0,9192	—
220α₁		1,0120	0,9164		1,0131	—		1,0131	—		1,0132	0,9174		1,0142	0,9166		1,0113	0,9157	—
310β	4	0,9932	0,9002																

a=2,8640±0,002 kX (Sample 1); a=2,8640±0,001 kX (Sample 2); a=2,8640±0,002 kX (Sample 3); a=2,8640±0,002 kX (Sample 4); a=2,8640±0,001 kX (Sample 5); a=2,8635±0,002 kX (Sample 12)

* d - diffuse line.

** w - wide line.

Table 1. Data from X-ray Patterns of Kamacite from the Sikhote-Alin' Meteorite.

with the edges of the unit cell of iron $a = 2.8605$ kX, which was accepted in the construction of the diagram of Figure 1.

We obtained clear-cut lines of different intensity in all cases of x-ray pictures of meteoritic iron that we studied. The number of lines on the x-ray patterns was not large (from 6 to 14 for different samples). When interpreting the x-ray patterns, we used the interplane distances given in the Roentgenometricheskiy opredelitel' mineralov (The Roentgenometric Detector of Minerals) (Ref. 8) as standard data for kamacite and taenite. It should be noted that the technique for obtaining x-ray patterns is considerably improved at present, so that our x-ray patterns have, as a rule, more lines than are given in the above-mentioned book. These additional lines were indexed, starting with the lattice parameter that thad been found, and were used to confirm the identification with kamacite or taenite.

The characteristics of x-ray patterns obtained with nickeliferous iron from the Sikhote-Alin' meteorite are presented in Table 1. As may be seen from the Table, all six of the studied samples contain kamacite, in which the edge of the unit cell $a = 2.8640$ kX in five samples and $a = 2.8635$ kX in sample No. 12.

As is well known, substitutional solid solutions, including kamacite, can have a superstructure, that is, ordered solid solutions. In this case the x-ray patterns of such a solid solution contain additional lines which are, so to speak, superstructure lines. In the formation of substitutional solid solutions, the atoms of the solute can displace any of the atoms of the solvent, being distributed in the lattice points in a wholly arbitrary manner. Such solid solutions are called disordered. But, as a result of slow cooling or prolonged annealing at definite temperatures, the structure of an alloy acquires a regular arrangement of the different atoms. The atoms of one metal are arranged in certain lattice points (for example, in the center of a cube). This distribution of the constitutents of an alloy can be described as a spatial lattice of atoms of one metal intruding into the lattice of atoms of a second metal. Such an ordered solid solution of superstructure differs from a solid solution and, at the same time, is not a new phase. The additional lines which appear in an x-ray pattern are obviously superstructure lines since they can be indexed, starting with the known and the doubled parameter of kamacite. Table 1 shows the indices which have been found for these lines. The nickel atoms in kamacite are located in the vertices of a simple cubic lattice interpenetrating the iron structure. The parameter of such kamacite is more precisely determined as doubled.

Thus, the samples of nickeliferous iron from the Sikhote-Alin' meteorite are kamacite with ordered structure. An uninterpreted line in sample No. 1 with low intensity and an inter-plane distance of 1.7576 kX

Meteorite	Kamacite, kX	Taenite, kX	Remarks
Coahuila (Fort Duncan) Hexahedrite	2.8640±0.0008	- -	- -
Hex River Mountains, hexahedrite	2.8644±0.0008	- -	- -
Chesterville, ataxite poor in nickel	2.8618±0.0006	3.632	Parameter of taenite calculated from one line (III)
Sao Juliao de Moreira, coarse octohedrite			
a) gray sections	2.8620±0.0003	3.652	
b) white sections	2.8647±0.0002	3.598	
Carlton, fine-structured octohedrite	2.8661±0.0015	3.583	
Tazewell, fine-structured octohedrite	2.8667±0.0007	3.583	
Bodaybo - octohedrite	2.861	3.570	X-ray picture taken in a camera with a diameter of 68 mm

Table 2. Parameters of Kamacite and Taenite from Meteorites.

should be ascribed to a random impurity.

The results of x-ray studies of samples of meteoritic iron from other meteorites are presented in Table 2. Taenite was discovered along with kamacite in five meteorites of the seven which were studied. It is necessary to note that superstructural lines appeared in x-ray patterns of these meteorites taken in large-diameter cameras. In particular, a superstructural line at 200α appeared in an x-ray pattern of the Coahuila meteorite. Superstructural lines which appeared in other x-ray patterns, if they were present, were not registered.

We calculated the percentage content of the nickel contained in the samples by the Mikheyev formula given above on the basis of the determined parameters of the unit cells of kamacites. The nickel content of the kamacites was also determined by the Bradley, Jay, and Taylor diagram (Figure 1). The results we obtained are presented in Table 3. As may be seen from the Table, the nickel contents in the kamacites determined by the parameters of the unit cells by these methods do not agree. Starting with the law derived by Mikheyev and the parameters of the cells we obtained, the meteorites should contain kamacites with a nickel content of more than 7 percent. This conclusion contradicts the generally accepted concept and the Bradley, Jay, and Taylor diagram compiled on the basis of studies of artificial alloys. We could not

determine the nickel content in all the meteorites under study with the aid of the diagram of Figure 1 since we encountered an unstudied two-phase region according to the determined cell parameter. It is also impossible to make use of the curve of the diagram for determining the percentage content of nickel in taenite from meteorites. The dimensions of the unit cell which were found for it are either larger than those obtained for artificial alloys or they fall in the region where the curve is bent so that two values are obtained.

Meteorite	According to Mikheyev		According to Bradley and Others (Figure 1)	
	Atomic %	Weight %	Atomic %	Weight %
Sikhote-Alin'				
Samples 1,2,3,4,5	6.73	7.05	5.2	5.47
Sample 12	5.51	5.80	4.4	4.61
Coahuila	6.73	7.05	5.2	5.47
Hex River Mountains	7.7	8.06	5.7	6.0
Chesterville	1.36	1.43	1.20	1.26
Sao Juliao de Moreira				
a) Gray sections	1.85	1.92	1.80	1.90
b) White sections	8.44	8.85	- -	- -
Carlton	11.85	12.40	- -	- -
Tazewell	13.31	13.95	- -	- -

Table 3. The Nickel Content of the Meteorites Under Study According to Data from X-ray Studies.

The work by M. I. D'yakonova (Ref. 2) gives the chemical analyses of the Sikhote-Alin' kamacites which we studied with x-rays. (All data presented later on analyses of the minerals in the Sikhote-Alin' meteorite have been taken from this work.)

Sample No. 1 contains 5.86 percent nickel by weight, sample No. 2 - 5.80, sample No. 3 - 6.14, and sample No. 4 - 6.09. The same work also gives a complete analysis of the nickeliferous iron in the Sikhote-Alin' meteorite which indicates that it contains 0.47 percent Co by weight and 0.03 percent Cu. It is obvious that these elements are included in the kamacite lattice as isomorphic admixtures, which is all the more true because their atomic radii are close to the value for iron and nickel. If we bear this in mind, then the discrepancy between the nickel content in the kamacites as determined chemically and as determined by x-rays through the Mikheyev formula is understandable. The value obtained by this formula reflects the nickel content and also that of cobalt and copper.

Ordinal No. of the line of the Debye powder pattern	I	da/n	dβ/n	Hydrogeothite		Hydrohematite		Taenite		Kamacite		
				I	da/n	I	da/n	I	da/n	I	hkl	da/n
1	4	4,89	4,43	—	—	—	—	—	—	—	—	—
2	1	4,56	4,14	2	4,613	—	—	—	—	—	—	—
3	1	4,35	3,95	—	—	—	—	—	—	—	—	—
4	10	4,157	3,768	10	4,178	—	—	—	—	—	—	—
5	1	3,673	3,329	—	—	6	3,680	—	—	—	—	—
6	1	3,435	3,114	—	—	—	—	—	—	—	—	—
7	4	3,320	3,009	3	3,385	—	—	—	—	—	—	—
8	3	2,943	2,667	1	2,975	—	—	—	—	—	—	—
9	1	2,750	2,493	—	—	10	2,694	—	—	—	—	—
10	9	2,686	2,435	8	2,690	—	—	—	—	—	—	—
11	4	2,572	2,331	3	2,580	—	—	—	—	—	—	—
12	4	2,506	2,271	—	—	8	2,511	—	—	—	—	—
13	10	2,446	2,217	10	2,450	4	2,435	—	—	—	—	—
14	1	2,278	2,065	—	—	—	—	—	—	—	—	—
15	3	2,249	2,038	4	2,253	—	—	—	—	6	110³	2,237
16	4	2,191	1,986	6	2,189	8	2,198	8	2,083	—	—	—
17	9	2,069	1,875	—	—	—	—	—	—	10	110	2,028
18	8	2,024	1,835	1	2,020	—	—	—	—	—	—	—
19	1	1,922	1,742	1	1,923	—	—	—	—	—	—	—
20	1	1,900	1,722	1	1,895	—	—	—	—	—	—	—
21	6	1,798	1,630	—	—	—	—	8	1,803	—	—	—
22	9	1,723	1,563	8	1,719	—	—	—	—	—	—	—
23	2	1,693	1,534	2	1,692	10	1,691	—	—	—	—	—
24	1	1,680	1,523	1	1,659	—	—	—	—	—	—	—

TABLE 4. INTERPRETATION OF X-RAY PATTERNS OF THE FUSED CRUST OF THE TAZEWELL METEORITE

Ordinal No. of the line of the Debye powder pattern	I	da/n	dβ/n	Hydrogeothite		Hydrohematite		Taenite		Kamacite		
				I	da/n	I	da/n	I	da/n	I	hkl	da/n
25	5	1,604	1,454	2	1,603	6	1,599	—	—	—	—	—
26	7	1,564	1,417	6	1,564	—	—	—	—	—	—	—
27	1	1,538	1,394	—	—	—	—	—	—	—	—	—
28	6	1,511	1,370	4	1,510	8	1,483	—	—	—	—	—
29	5	1,475	1,337	—	—	8	1,450	—	—	—	—	—
30	5	1,455	1,319	4	1,454	—	—	—	—	4	200	1,432
31	3	1,422	1,289	2	1,423	—	—	—	—	—	—	—
32	3	1,397	1,266	2	1,397	—	—	—	—	—	—	—
33	2	1,370	1,242	—	—	—	—	—	—	—	—	—
34	3	1,358	1,231	1	1,362	—	—	—	—	—	—	—
35	4	1,318	1,195	1	1,319	6	1,311	—	—	—	211β	—
36	2	1,291	1,171	1	1,292	—	—	8	1,275	—	—	—
37	5	1,268	1,150	1	1,266	4	1,257	—	—	—	—	—
38	2	1,245	1,128	1	1,246	3	1,189	—	—	—	—	—
39	2	1,199	1,087	—	—	—	—	—	—	—	—	—
40	4	1,169	1,060	—	—	—	—	—	—	10	211	1,170
41	1	1,154	1,046	—	—	—	—	—	—	—	—	—
42	1	1,146	1,038	—	—	3	1,139	—	—	—	—	—
43	3	1,129	1,023	1	1,127	—	—	—	—	—	—	—
44	1	1,118	1,013	—	—	—	—	—	—	—	—	—
45	1	1,097	0,995	—	—	4	1,057	—	—	—	—	—
46	7	1,082	0,980	—	—	—	—	8	1,089	—	220β	—
47	1	1,070	0,970	—	—	—	—	—	—	—	—	—
48	1	1,055	0,957	—	—	—	—	8	1,049	—	—	—
49	3	1,044	0,946	—	—	—	—	—	—	—	—	—
50	1	1,035	0,938	—	—	—	—	—	—	—	—	—

TABLE 4 (Continued)

Nevertheless, it is necessary to state that it is impossible at present to obtain a reliable determination of the content of the constituents in nickeliferous iron from meteorites by the dimensions of the unit cell.

In concluding this section of the article it is necessary to point out the following:

a) when the parameters of the kamacite are small, the parameter of the taenite increases; the edge of the unit cell in taenite can be considerably larger than that observed in artificial alloys; b) when the taenite content of the meteorite is increased, the parameter of the kamacite is increased and the parameter of the taenite is decreased.

These conclusions must be considered to be of a provisional nature since the x-ray studies were conducted with a small number of samples.

The Crust of the Tazewell Meteorite. As previously mentioned, this meteorite had a fused crust whose composition was determined by the x-ray method. Table 4 gives the results of measurements of the lines in the Debye powder patterns and their interpretation.

Of the 50 lines found on the photograph, 22 are associated with hydrogoethite, 13 with hydrohematite (turgite), 6 lines with kamacite, and 5 with taenite. Thus, hydrogoethite and hydrohematite were formed in the fused crust of the meteorite under conditions prevailing at the earth's surface along with the kamacite and taenite which existed in the crust. The parameters of the latter, as calculated in accordance with the data from the x-ray pattern, correspond to those for kamacite and taenite from the main mass of this meteorite, but they are less accurate than the values given above, since the x-ray pattern of the given sample was taken with a camera with a diameter of 68 mm.

Ten lines with an intensity of 1 remained unsolved. This is explained obviously by the fact that the available standards for hydrogoethite and hydrohematite go back to 1938 but the techniques now used for taking the pictures have been improved and the x-ray pictures showed more lines than the standards. The lines for hydrogoethite and hydrohematite were not indexed.

Now, let us proceed to elucidate the results of x-ray studies of the minerals found in the Sikhote-Alin' meteorite.

Chromite (Sample 8). Its chemical composition was as follows (weight percent):

Fe - 12.38, Cr - 48.74, Mg - 7.16, or if recomputed for oxides: FeO -

15.91, Cr_2O_3 - 71.23, MgO - 11.87; total 99.01.

Table 5 contains an interpretation of the x-ray pattern taken with this sample. As may be seen from the Table, sample **No**. 8 contains chromite with the edge of the unit cell a = 8.329+0.001 kX and a considerably smaller, but noticeable quantity of a substance with the chemical composition $3Cr_2O_3 \cdot Fe_2O_3$.

Ordinal No. of the Lines of the Debye Powder Pattern	Sample 8 Chromite			Chromite				3Cr₂O₃·Fe₂O₃ *	
	I	dα/n	dβ/n	I	dα/n	hkl	a	I	dα/n
1	2	2,943	(2,667)	6	2,95	220	8,324	—	—
2	1	(2,768)	2,509			311β	8,321	—	—
3	3	2,664	(2,415)	—	—	—	—	8	2,67
4	1	2,578	(2,336)	—	—	—	—	—	—
5	10	2,513	(2,278)	10	2,516	311	8,335	8	2,49
6	1	2,404	(2,179)			222	8,328	—	—
7	1	(2,301)	2,086			400β	8,344	—	—
8	1	2,181	(1,977)	—	—	—	—	8	2,18
9	7	2,081	(1,887)	7	2,085	400	8,324	—	—
10·	1	1,818	(1,628)	—	—	—	—	8	1,820
11	1	(1,768)	1,603			333β	8,330	—	—
12	1	1,701	(1,542)			422	8,333	—	—
13	7	1,673	(1,517)	—	—	—	—	10	1,672
14	7	1,604	(1,454)	9	1,605	333	8,335	—	—
15	9	1,473	(1,335)	9	1,475	440	8,333	9p **	1,467
16	2	1,435	(1,301)	—	—	—	—	9p	1,435
17	1	1,295	(1,174)	—	—	—	—	9p	1,295
18	1	1,270	(1,151)	5	1,272	533	8,328	—	—
19	1	1,255	(1,138)	3		622	8,325	9p	1,244
20	1	1,210	(1,097)	—	—	—	—	7p	1,213
21	1	1,201	1,809	3	1,205	444	8,321	7p	1,200
22	⌈1	1,411	(1,010)	3	1,115	642	8,336	—	—
23	⌊4	1,084	(0,983)	6	1,087	553	8,326	—	—
24	⌊2	1,041	(0,943)	3	1,043	800	8,328	—	—

$a_{cp} = 8,329 \pm 0,001$ kX

TABLE 5
INTERPRETATION OF THE X-RAY PATTERN OF SAMPLE 8
FROM THE SIKHOTE-ALIN' METEORITE

* According to Wretblad (Ref. 15)

** d - diffuse line

In accordance with the mathematical law derived by Mikheyev

(Refs. 9, 11) for spinellids and judging by the value for the edge of the chromite unit cell, the chemical formula for the given chromite should be $(Mg, Fe)Cr_2O_4$, where magnesium and iron ions are present in equal numbers.

No substance with the chemical composition $3Cr_2O_3 \cdot Fe_2O_3$ has been yet encountered among the minerals of the earth's crust; thus it is a new mineral in this respect. It was identified through a standard x-ray diffraction pattern given in the first supplement to the American Card File of X-Ray Diffraction Data. This x-ray pattern was compiled in accordance with data from Wretblad (Ref. 15), who studied an artificial compound of this composition.

Table 5 implies that the lines remaining from chromite are well interpreted by this substance, for which lines with $d\alpha/n = 1.673(7)$, 2.664(3), and 1.435(2) are characteristic, so that its presence in sample No. 8 should be considered proved by x-rays. The card indicates that this substance has a rhombohedric cell: $\alpha = 55°28'$ and a = 5.362 kX.

In order to isolate an independent mineral with this composition it is necessary to study its physical and other properties along with x-ray certification.

It should be pointed out that this substance was determined for the first time in sample 8 in accordance with preliminary x-ray data from V. I. Mikheyev.

It will be essential to conduct a painstaking study of sample 8 from the Sikhote-Alin' meteorite.

Troilite (sample 7). Chemical analysis of a part of this sample yielded the following results (percent of weight): Fe - 60.78, Cu - 0.04, S - 36.41, Cr - 2.08. Total 99.31.

The interpretation of an x-ray pattern of this sample is given in Table 6. As may be seen from the Table, sample 7 contains only troilite. The x-ray pattern shows 35 fairly clear-cut lines, which is considerably greater than on the standard Debye powder pattern for the Augustinovka meteorite. The Table contains a comparison of x-ray patterns which implies that all the lines of the sample under study, except the last diffuse line, are satisfactorily indexed on the basis of the calculated parameters for troilite.

The dimensions of the hexagonal unit cell of the troilite from the sample from the Sikhote-Alin' meteorite turned out to be a = 5.965

kX, c = 11.538 kX.

·The parameter a of the cell was computed from the inter-plane

distances of the reflections: $11\bar{2}0$, $30\bar{3}0\beta$, $30\bar{3}0$, $32\bar{5}0$. The parameter c was computed from the reflections 0006 and 0008.

Troilite with inclusions of other minerals (sample 6). Chemical analyses exist for two samples of this material which showed (percent of weight):

Sample 1: Fe - 62.46, Cu - 0.05, S - 34.65, Cr - 1.06;
Total 98.22.
Sample 2: Fe - 62.84, Cu - 0.07, S - 34.33, Cr - 1.08;
Total 98.32.

The results obtained from measuring the lines of an x-ray pattern of this sample and its interpretation are presented in Table 7. This Table implies that this sample of the Sikhote-Alin' meteorite contains troilite with an admixture of chromite. The parameters of the troilite are as follows: a = 5.925 kX, c = 11.562 kX. The edge of the unit cell of chromite is: a = 8.344+0.004 kX, which corresponds to the chemical formula $FeCr_2O_4$. A comparison of the parameters of the troilite in samples 6 and 7 indicates some difference which is obviously explained by isomorphic substitutions in this mineral. The nature of these substitutions is not clear. The x-ray pattern of this sample has four lines with the low intensity 1 which remain uninterpreted.

Schreibersite (sample 9 and specimen 2052/33). Chemical analysis showed (percent of weight): Fe - 69.73, Ni - 14.64, Co - 0.18, P - 15.64; total - 100.19.

The x-ray pattern taken of this sample had 55 clear lines. The calculation of the x-ray pattern is presented in Table 8. We did not have a standard x-ray pattern for schreibersite at our disposal. All the plane lattices of the x-ray picture were indexed in order to confirm the presence of schreibersite in this sample. The parameters given in the manual by A. G. Betekhtin (Ref. 1) were used as the initial data for schreibersite (tetragonal syngony). Table 8 implies that all the lines on the x-ray picture were indexed; that is, all the plane meshes received corresponding indices. Thus, this sample contains only schreibersite. The parameters of the schreibersite photographed here were made more precise in the process of indexing, turning out to be: a = 9.065+0.002 kX, c = 4.444 kX. The size of the unit cell along the a axis was determined by the inter-plane distances from the plane lattices with the following indices: 400, 330, 420, 510, 530, 620, 640, 820, and 660. The parameter along the c axis was found by the reflection from the plane lattice 004.

Ordinal Nbr. of the lines of the Debye powder pattern	hkil	Sample 7			Troilite from the Augustinovka Meteorite	
		I	da/n	dβ/n	I	da/n
1	11$\bar{2}$0β	1	(3,26)	2,958	1	(3,294)
2	11$\bar{2}$0	8	2,983	2,704	6	2,968
3	11$\bar{2}$2β	3	(2,935)	2,661	—	—
4	11$\bar{2}$2	9	2,658	2,409	7	2,644
5	10$\bar{1}$4	3	2,516	2,281	1	2,531
6	11$\bar{2}$4β	7	(2,305)	2,090	5	(2,304)
7	0006β	2	(2,148)	1,947	—	—
8	11$\bar{2}$4	10	2,093	1,897	10	2,085
9	0006	6	1,923	1,743	4	1,921
10	30$\bar{3}$0β	3	(1,900)	1,722	—	—
11	11$\bar{2}$6β	1	1,800	1,631	1	(1,809)
12	21$\bar{3}$3	1	1,747	1,583	2	1,755
13	30$\bar{3}$0	9	1,722	1,561	9	1,720
14	11$\bar{2}$6; 21$\bar{3}$4	5	1,637	1,484	5	1,637
15	11$\bar{2}$7β	3	(1,594)	1,445	—	—
16	21$\bar{3}$5	2	1,498	1,357	—	—
17	0008	7	1,463	1,326	5	1,472
18	11$\bar{2}$7	5	1,445	1,309	3	1,445
19	30$\bar{3}$6β	2	(1,421)	1,288	—	—
20	40$\bar{4}$3β	1	(1,346)	1,220	—	—
21	22$\bar{4}$4	7	1,329	1,205	8	1,328
22	11$\bar{2}$8	4	1,316	1,193	6	1,319
23		3 {	1,285	1,165	2	1,279
24	30$\bar{3}$6	2 {	1,270	1,151		
25	40$\bar{4}$3; 31$\bar{4}$5	5 {	1,231	1,116	3	1,223
26			1,221	1,106		
27	32$\bar{5}$0; 40$\bar{4}$4		1,184	1,073	4	1,182
28		5 {	1,178	1,068		
29	41$\bar{5}$4β; 40$\bar{4}$8β	1p*	(1,160)	1,051	—	—
30	41$\bar{5}$0	4	1,132	1,026	—	—
31	30$\bar{3}$8	8	1,115	1,011	6	1,117
32	41$\bar{5}$2	5	1,105	1,002	3	1,106
33	1.1.$\bar{2}$.10	3p	1,090	0,988	2	1,090
34	41$\bar{5}$4; 40$\bar{4}$8	7	1,051	0,952	6	1,051
35	—	3p	1,022	0,926	—	—

* d- diffuse line

TABLE 6

INTERPRETATION OF THE X-RAY PATTERN OF SAMPLE 7
FROM THE SIKHOTE-ALIN' METEORITE

Ordinal Nbr. of the lines of the Debye powder pattern	Sample 6				Sample 7 Troilite		Chromite		
	I	da/n	dβ/n	hkil	I	da/n	I	da.n	hkl
1	1	5,31	4,82	10$\bar{1}$0	—	—	—	—	—
2	6	2,965	2,688	11$\bar{2}$0	8	2,983	6	2,95	220
3	2	(2,772)	2,513	10$\bar{1}$43	—	—	—	—	—
4	8	2,658	2,409	11$\bar{2}$2	9	2,658	—	—	—
5	8	2,522	2,286	10$\bar{1}$4	3	2,516	10	2,516	311
6	6	(2,307)	2,091	11$\bar{2}$48	7	(2,305)	—	—	—
7	10	2,090	1,894	11$\bar{2}$4	10	2,093	7	2,085	400
8	2	1,927	1,746	0006	6	1,923	—	—	—
9	1	(1,903)	1,725	30$\bar{3}$03	3	(1,900)	—	—	—
10	1	1,771	1,605	—	—	—	—	—	—
11	1	1,744	1,581	21$\bar{3}$3	1	1,747	—	—	—
12	8	1,720	1,559	30$\bar{3}$0	9	1,722	—	—	—
13	5	1,629	1,477	11$\bar{2}$6; 21$\bar{3}$4	5	1,637	—	—	—
14	7	1,607	1,457	11$\bar{2}$7	3	1,594	9	1,605	333
15	1	1,502	1,361	21$\bar{3}$5	1	1,498	—	—	—
16	7	1,475	1,337	—	—	—	9	1,475	440
17	4	1,467	1,330	0008	7	1,463	—	—	—
18	1	1,443	1,308	11$\bar{2}$7	5	1,445	—	—	—
19	1	(1,409)	1,277	30$\bar{3}$63	2	1,421	—	—	—
20	1	1,383	1,254	—	—	—	—	—	—
21	1	(1,342)	1,223	40$\bar{4}$38	1	(1,346)	—	—	—
22	5	1,329	1,205.	22$\bar{4}$4	7	1,329	—	—	—
23	2	1,316	1,193	11$\bar{2}$8	4	1,316	—	—	—
24	4	1,271	1,152	30$\bar{3}$6	2	1,270	5	1,272	533
25	1	1,261	1,143	—	—	—	—	—	—
26	1w**	1,224	1,110	40$\bar{4}$3; 31$\bar{4}$5	5 {	1,231 ; 1,221	—	—	—
27	1w	1,202	1,090	—	—	—	3	1,205	444
28	1	1,182	1,071	32$\bar{5}$0; 40$\bar{4}$4	5 {	1,184 ; 1,178	—	—	—
29	1	(1,168)	1,058	41$\bar{5}$48	1p	1,160	—	—	—
30	1	1,150	1,043	—	—	—	—	—	—
31	1	1,130	1,024	41$\bar{5}$0; 32$\bar{5}$3	4	1,132	—	—	—
32	7	1,116	1,011	30$\bar{3}$8	8	1,115	3	1,115	642
33	2	1,107	1,003	41$\bar{5}$2	5	1,105	—	—	—
34	6	1,087	0,985	11$\bar{2}$.10	3p*	1,090	6	1,087	553;731
35	3	1,051	0,952	41$\bar{5}$4; 40$\bar{4}$8	7	1,051	—	—	—
36	4	1,042	0,945	—	—	—	3	1,043	800

* d – diffuse line
** w – wide line

TABLE 7

INTERPRETATION OF THE X-RAY PATTERN OF SAMPLE 6 FROM
THE SIKHOTE-ALIN' METEORITE

Ordinal Nbr. of the lines of the Debye powder pattern	hkl	i	$d\alpha/n$	$d\beta/n$	Ordinal Nbr. of the lines of the Debye powder pattern	hkl	I	$d\alpha/n$	$d_{\beta/n}$
1	211	2	2,998	2,717	31	541	1p	1,351	1,225
2	301β	1	(2,765)	2,507	32	303	2	1,332	1,208
3	?	1	2,652	2,404	33	721	1	1,321	1,198
4	301	6	2,506	(2,271)	34	631	5	1,292	1,171
5	321β	5	(2,419)	2,192	35	323	9	1,277	1,158
6	330β	2	(2,363)	2,133	36	640	4	1,257	1,139
7	112β	3	(2,321)	2,104	37	701	4	1,242	1,126
8	400	1	2,270	2,057	38	413	7	1,230	1,115
9	420β	2	(2,230)	2,021	39	622	6	1,206	1,093
10	321	10	2,190	(1,985)	40	721	7	1,197	1,085
11	330	7	2,137	1,937	41	433	7	1,148	1,041
12	112	7	2,104	1,907	42	831β	1	(1,136)	1,030
13	420	8	2,028	1,838	43	651	8	1,122	1,017
14	411	10	1,973	1,788	44	004; 523	9	1,111	1,007
15	312β	1	(1,942)	1,760	45	820	2	1,099	0,997
16	222	7	1,829	1,658	46	114; 642	7	1,094	0,991
17	510	8	1,779	1,613	47	811 741	4	1,088	0,987
18	312	8	1,757	1,593					
19	530β	1	(1,712)	1,552	48	424β	1	(1,075)	0,975
20	431; 501	7	1,678	1,521	49	660	1	1,068	0,968
21	620β	1	1,593	1,444	50	921β; 711β	1	(1,057)	0,958
22	521	1	1,572	1,425					
23	530	3	1,556	1,411	51	224; 732 613	8	1,051	0,953
24	332	1	1,537	1,393					
25	422	4	1,501	1,360	52	851β	3	(1,038)	0,941
26	103	3	1,465	1,328	53	831	8	1,030	0,934
27	620	4	1,433	1,299	54	733β	1	(1,024)	0,928
28	611	6	1,411	1,279	55	802	4	1,012	0,917
29	213	1	1,391	1,261					
30	701β	1	(1,370)	1,242					

TABLE 8

X-RAY PATTERN OF SCHREIBERSITE FROM THE SIKHOTE-ALIN' METEORITE

Rabdite (samples 10 and 11). Chemical analysis showed weight percent: Ni - 29.8, P - 15.2.

X-ray patterns taken of these two samples turned out to be identical. Therefore, the calculation and interpretation of the Debye powder patterns which are presented in Table 9 were carried out only for

Ordinal Nbr. of the lines of the Debye powder pattern	Sample 11				Schreibersite	
	hkl	*I*	*dα/n*	*dβ/n*	*I*	*dα/n*
1	110	1	6,71	6,08	—	—
2	211	2	2,990	2,711	2	2,998
3	301β	1	(2,736)	2,480	1	(2,765)
4	301	6	2,487	2,254	6	2,506
5	321β	4	(2,407)	2,182	5	(2,419)
6	330β	1	(2,345)	2,126	3	2,363
7	112β	3	(2,316)	2,099	3	(2,321)
8	400	1	2,266	2,053	1	2,270
9	420β	1	(2,220)	2,013	2	(2,230)
10	321	10	2,180	1,976	10	2,190
11	330	7	2,128	1,928	7	2,137
12	112	8	2,102	1,906	7	2,104
13	420	8	2,018	1,829	8	2,028
14	411	10	1,968	1,784	10	1,973
15	312β	1	(1,937)	1,756	1	(1,942)
16	222	7	1,826	1,656	7	1,829
17	510	6	1,771	1,605	8	1,779
18	312	8	1,753	1,589	8	1,757
19	431; 501	6	1,671	1,514	7	1,678
20	620β	2	(1,588)	1,440	1	1,593
21	521	1	1,567	1,420	1	1,572
22	530	3	1,542	1,398	3	1,556
23	422	3	1,496	1,356	4	1,501
24	103	1	1,463	1,326	3	1,465
25	620	3	1,425	1,291	4	1,433
26	611	6	1,405	1,273	6	1,411
27	213	1	1,386	1,256	1	1,391
28	541	1m	1,351	1,225	1p	1,351
29	303	1m	1,325	1,201	2	1,332
30	631	2	1,290	1,169	5	1,292
31	323	8	1,275	1,155	9	1,277
32	640	2	1,250	1,133	4	1,257
33	721	1	1,238	1,123	4	1,242
34	413	8	1,228	1,113	7	1,230
35	622	8	1,204	1,091	6	1,206
36	721	8	1,193	1,082	7	1,197
37	433	8	1,146	1,039	7	1,148
38	831β	2	(1,121)	1,016	1	1,136
39	651	8	1,115	1,010	8	1,122
40	004	8	1,106	1,003	9	1,111
41	114; 642	8	1,091	0,989	7	1,094
42	224,732; 613	6m	1,049	0,951	8	1,051
43	851β	2	(1,037)	0,940	3	(1,038)
44	831	3	1,030	0,934	8	1,030
45	733β	3	(1,026)	0,930	1	(1,024)

TABLE 9

INTERPRETATION OF THE X-RAY PATTERN OF SAMPLE 11
FROM THE SIKHOTE-ALIN' METEORITE

sample 11. The table shows that 45 fairly clear-cut lines were obtained from the x-ray picture of this sample. A comparison of the x-ray patterns of sample 11 and schreibersite indicated their similarity. Some difference in the inter-plane distances in the sample under study indicates a somewhat different relationship of the isomorphic constituents.

The computed parameters of the unit cell of rabdite from sample 11 turned out to be: $a = 9.022 \pm 0.004$ kX, $c = 4.424$ kX; that is, they are somewhat smaller than the values for schreibersite. In connection with the nickel content of rabdite, which is greater than that of schreibersite and its ionic radius, which in turn is less than that of iron ions, the difference in the inter-plane distances and the sizes of the unit cells of rabdite and schreibersite are understandable.

Thus, these two minerals are intermediate members of the single isomorphic series $(Fe, Ni)_3 P$.

II. Carbonaceous Chondrites

Samples from the Cold Bokkeveld and Staroye Boriskino Meteorites. The x-ray pattern taken of samples from these meteorites turned out to be alike, both in the nature of the arrangement of their lines and in the diffused nature of the lines, which disappeared completely in the peripheral portions of the x-ray pattern. The results obtained from interpretation of the x-ray pattern are presented in Table 10; since the x-ray patterns are of the same type, they are mutually comparable.

We were not able to interpret the composition of the meteorites since not one of the standards available to us coincided satisfactorily with the x-ray patterns we had obtained. We can state only that a like substance was present in both meteorites which possessed the same structure and chemical composition. Some fluctuations in inter-plane distances can be explained by isomorphic substitutions in the mineral.

All lines of the x-ray pattern of the Cold Bokkeveld coincide with the lines of the x-ray pattern of the Migey meteorite presented in the article by V. I. Mikheyev and A. I. Kalinin (Ref. 10); that is, the mineral is the same. In accordance with the works of L. G. Kvasha (Refs. 3, 4, 5), who was first to discover hydrous silicate in meteorites and made a microscopic study of it and also in accordance with data from x-ray studies, this mineral belongs with minerals of the chlorite-serpentine series: that is, to a group of minerals which have not been adequately studied by x-ray methods. It is necessary to verify Mikheyev's conclusion (Ref. 10) that the mineral from these meteorites is, according to x-ray data, associated most closely with antigorite serpentine with a considerable ferrous iron content.

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The x-ray pattern of the Cold Bokkeveld meteorite indicates the presence of lines of iron, but since the edge portion of the Debye powder pattern has almost no lines, in particular iron lines which are necessary in this region, one cannot be certain of this. The carbonaceous material in the meteorites is apparently amorphous.

Ordinal Nbr. of the lines of the Debye powder pattern	Cold Bokkeveld			Staroye Boriskino		
	I	$d\alpha/n$	$d\beta/n$	I	$d\alpha/n$	$d\beta/n$
1	2	7,88	7,14	2	7,86	7,12
2	9	7,11	6,44	9	7,14	6,47
—	—	—	—	1	5,00	4,53
3	1	4,61	4,18	1	4,56	4,14
4	3	3,88	3,52	2	3,89	3,53
5	10	3,56	3,23	10	3,56	3,23
6	1	3,31	3,00	—	—	—
7	1	3,17	2,872	—	—	—
8	3p*	3,01	2,724	3	3,01	2,727
9	1	2,873	2,604	—	—	—
10	2	2,770	2,511	2	2,781	2,520
11	2	2,696	2,444	2	2,678	2,427
12	10	2,522	2,286	10	2,518	2,282
13	5	2,450	2,220	—	—	—
14	—	—	—	1	2,292	2,078
14	3	2,253	2,042	—	—	—
15	4	2,155	1,953	5	2,156	1,954
16	3	2,021	1,832	—	—	—
17	1	1,920	1,744	1	1,925	1,745
18	1	1,845	1,672	—	—	—
19	4	1,779	1,613	3p	1,792	1,624
20	5	1,744	1,581	1	1,742	1,579
21	1p	1,672	1,516		1,680	1,523
22	1p	1,610	1,459	—	—	—
23	6	1,581	1,433	3	1,571	1,624
24	6	1,526	1,383		1,532	1,553
25	4	1,488	1,349	—	—	—
26	4	1,470	1,333	—	—	—
27	3p*	1,430	1,297	1p	1,436	1,301
28	1	1,387	1,257	—	—	—
29	2	1,355	1,228	—	—	—
30	1	1,321	1,197	2p	1,325	1,201
31	2	1,306	1,184	—	—	—
32	1	1,261	1,143	—	—	—

* d- diffuse line

TABLE 10

X-RAY PATTERN OF THE COLD BOKKEVELD AND STAROYE BORISKINO METEORITES

Ordinal Nbr. of the lines of the Debye powder pattern	White Substance			Black Substance			Magnetite	
	I	dα/n	dβ/n	I	dα/n	dβ/n	I	dα/n
—	—	—	—	1	4,89	4,43	—	—
—	—	—	—	2	4,53	4,10	—	—
1	1	4,26	3,86	1	4,28	3,88	1	4,21
2	2	3,91	3,55	—	—	—	—	—
3	1	3,52	3,19	—	—	—	—	—·
4	1	3,29	2,981	—	—	—	3	(3,31)
5	2	3,06	2,771	1	3,06	2,774	—	—
6	7	2,973	2,694	7	2,968	2,690	6	2,99
7	1	2,880	2,611	1	2,876	2,606	—	—
8	7	2,785	2,524	5	2,785	2,524	5	(2,807)
9	1	2,637	2,390	—	—	—	—	—
10	10	2,532	2,295	10	2,532	2,295	10	2,541
11	4	2,471	2,240	1	2,451	2,224	3	2,428
12	1	(2,314)	2,098	1	(2,310)	2,094	3	(2,310)
13	4	2,268	2,056	—	—	—	—	—
14	1	2,163	1,961	—	—	—	—	—
15	7	2,099	1,902	8	2,094	1,898	7	2,098
16	1	1,938	1,757	—	—	—	—	—
17	1	1,880	1,704	1	1,880	1,712	2	1,884
18	7	1,751	1,587	3	1,780	1,614	4	1,785
19	7	1,711	1,551	4	1,711	1,551	5	1,710
20	1	1,687	1,529	—	—	—	—	—
21	1	(1,635)	1,482	1	(1,635)	1,482	2	(1,632)
22	8	1,613	1,462	8	1,614	1,463	9	1,612
23	5p*	1,534	1,390	7	1,532	1,388	—	—
24	9	1,480	1,342	9	1,482	1,343	9	1,479
25	1	1,442	1,307	—	—	—	—	—
26	1	1,417	1,284	—	—	—	2	1,411
27	1	1,394	1,263	—	—	—	—	—
28	3p	1,351	1,225	—	—	—	—	—
29	3	1,327	1,203	3	1,328	1,203	3	1,325
30	1	1,315	1,192	—	—	—	—	—
31	6	1,278	1,159	6	1,279	1,159	5	1,277
32	1	1,264	1,146	2	1,265	1,146	2	1,264
33	3	1,210	1,096	2	1,211	1,098	3	(1,209)
34	6	1,119	1,014	5	1,121	1,016	4	1,119
35	9	1,091	0,989	9,	1,092	0,989	8	1,091
36	7	1,047	0,949	6	1,048	0,950	6	1,047

* d-diffuse line

TABLE 11

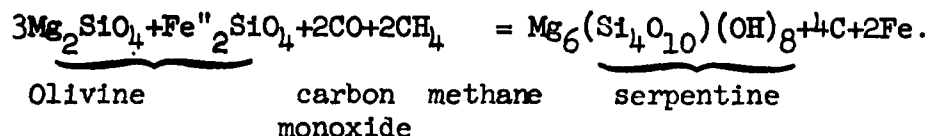X-RAY PATTERNS OF TWO SAMPLES FROM THE ORGUEIL METEORITE

The Orgueil Meteorite. Two samples were taken from this meteorite. One sample of the material was white, the other black. The x-ray patterns taken of both samples turned out to be alike, therefore their joint computation and interpretation are given in Table 11. The data presented here imply that both samples contain magnetite, the lines of

which are given in the Table. The remaining lines of the x-ray pattern coincide with lines of the mineral from the Cold Bokkeveld, Staroye Boriskino, and Migey meteorites in respect to their inter-plane distances. Thus, a mineral of the chlorite serpentine type is present in this meteorite. The difference in the values of the inter-plane distances of the compared x-ray patterns of this mineral is explained by different types of isomorphic substitutions of their cations.

Towards the Question of the Formation of Hydrous Silicates in Meteorites

The presence of these minerals in carbonaceous chondrites is an established fact now. These minerals are formed from olivine, which was established through microscopic study. However, it is scarcely probable that the transformation of the olivine in meteorites into hydrous silicate took place under the action of water. Even if one regards meteorites as fragments of a planet which existed formerly and revolved around the sun in an orbit between Mars and Jupiter, he must consider that such a planet must have been without oxygen, so that there could have been no water.

V. I. Mikheyev suggested a scheme for the transformation of olivine into hydrous silicate under the action of methane and carbon monoxide, whose presence is most probable on such celestial bodies and which might be contained in the atmosphere of a planet and also be discharged from its depths. The reaction takes place in the following scheme:

$$3Mg_2SiO_4 + Fe''_2SiO_4 + 2CO + 2CH_4 = Mg_6(Si_4O_{10})(OH)_8 + 4C + 2Fe .$$

Olivine   carbon   methane   serpentine
               monoxide

Carbon and native iron are also formed as a result of this reaction along the hydrous silicate. It is obvious that such minerals as magnetite could be formed instead of iron with different ratios of the reacting components.

According to the scheme set forth here, one should observe a definite ratio of water and carbon in the reaction products, namely: there are four atoms of carbon for every four molecules of water in carbonaceous meteorites. If we turn to weight ratios, we obtain the percentages by weight of water to the percentages of carbon = $4 \times 18 : 4 \times 12 = 72 : 48 = 1.5$.

Thus, the water content by weight in carbonaceous meteorites should be approximately one and one-half times greater than that of carbon.

On the basis of careful chemical and other analyses of ten

carbonaceous meteorites, Boato (Ref. 12) gives a water-to-carbon ratio which is close to the above figure. According to his figures, the ratio of the percentages by weight of water to the percentages by weight of carbon varies within narrow limits from 1.13 to 2.0, with an average of 1.42.

Apparently reactions similar to that described above occurred in nature, not only on celestial bodies, but also in the earth's crust. Serpentinization of olivine-containing rocks can take place in the deep parts of the earth's crust in accordance with this scheme.

This reaction should be reproduced experimentally under laboratory conditions, and the products obtained should be studied. Accomplishing this work should not give rise to special technical difficulties.

Conclusion

The application of x-ray methods to the study of meteorites makes it possible to determine their composition more accurately, also to establish patterns in the structure of meteoritic minerals in connection with their chemical composition. All this makes it possible to reveal more profoundly the nature of such material, thus aiding in interpretation of mineral associations in meteorites and in the earth's crust and in establishing their crystallographic and mineralogical patterns.

It will be necessary to conduct x-ray diffraction pattern investigations of kamacite and taenite from meteorites which must be selected carefully and to carry out chemical analyses of individual fractions in order to find the dependence of the parameters of the unit cells of these minerals on their chemical composition.

It will also be necessary to establish an x-ray diffraction standard for meteoritic minerals. When such a standard is available, x-ray diffraction methods will constitute one of the basic means for studying the composition of meteorites. The application of such methods to this field is also conditioned by the fact that the investigator is necessarily restricted to extremely small quantities of material.

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V. AN X-RAY STUDY OF THE FUSED CRUST OF THE KUNASHAK STONE METEORITE[*]

by V. D. Kolomenskiy

Russian Text Pages 36-99.

This article is a continuation of a study of the Kunashak stone meteorite, which has been studied by a number of investigators (Refs. 2, 6, 7, 8, 17, 18, 19, 20, 21, 22, and others) and is a direct continuation of the article by I. A. Yudin, "The Fused Crust of the Kunashak Stone Meteorite," published in 1955 (Ref. 20).

The authors acquired three samples from the Ural'sk Geological Museum in 1956 - 1958 with the purpose of conducting a mineralogical study of the fused crust of the Kunashak meteorite. Two of them were subjected to detailed x-ray study. All samples of the fused crust are powder of a dark gray color in which rare small grains cf nickeliferous iron of a light gray could be seen under a reading glass.

We separated the magnetic fraction consisting of nickeliferous iron, oxymagnetite, and IOTSIT (Transliterated, possibly josite) with a magnet. The magnetic fraction amounted to about 0.5 percent of the total quantity of powder.

The nickeliferous iron was in the form of small, irregular, symmetrical grains of angular shape, measuring up to 0.1 mm. When the magnetic fraction was placed on a biscuit and pulverized with another biscuit, an outline of black color characteristic of magnetite was obtained.

Debye powder patterns were taken in cameras with a diameter of 68.00 mm. The source of the rays was an ionic x-ray tube (λ_α = 1.934 kX, λ_β = 1.753 kX) with an iron anode operating at a voltage of 35 kv and with a current of 8 ma. Exposures were two hours under those conditions. The distances between symmetrical lines on the pictures were measured with a half-millimeter scale. The intensity of the lines(I)was evaluated by a ten-number scale in which the brightest line was assigned the number 10 and the weakest, scarcely distinguishable on the picture was assigned the number 1.

Corrections for absorption were introduced with rock salt (a = 5.6285 kX) by means of a picture of the material under study mixed with 20 percent of sodium chloride.

Both samples yielded satisfactory Debye powder patterns. An

[*]Commas in tables and graphs represent decimal points.

Ordinal No. of the line of the Debye powder pattern	I	dα/n	dβ/n	Olivine			Enstatite		Magnetite				Kamacite **			
				I	dα/n	hkl	I	dα/n	I	dα/n	hkl	a	I	dα/n	hkl	a
1	1	5,122	4,642	4	5,07	020										
2	1	4,293	3,892	2	4,29	110										
3	4	4,132	3,746	1	4,04	101β										
4	7	3,880	3,517	7	3,87	021			1	4,21						
5	2	3,732	3,383	4	3,716	101										
6	7	3,484	3,158	6	3,491	111; 120	7	3,50								
7	4	3,320	3,009	3	3,333	030	7	3,31	3	(3,31)						
8	4	3,152	2,857				10	3,17								
9	1	(3,040)	2,755	4	(3,058)	130β										
10	5	2,970	2,692	5	2,995	002			6	2,99	220	8,399				
11	2	2,855	2,588				9	2,883								
12	10	2,761	2,503	9	2,770	130										
13	3	2,715	2,461	3	(2,715)	112β	6	2,700	5	(2,807)						
14	2	2,637	2,390													
15	1	2,587	2,345													
16	10	2,509	2,274	10	2,515	131	9	2,539	10	2,541						
17	10	2,453	2,224	10	2,455	112	9	2,483	3	2,428						
18	1	(2,374)	2,152													
19	2	2,347	2,127	2	2,350	041										
20	2	2,314	2,098	1	2,316	210			3	(2,310)	400β	8,392				
21	8	2,267	2,055	9	2,253	140; 122?										
22	2	2,250	2,040										4	(2,245)	110β	2,885

Table 1. An Interpretation of the Composition of Sample 1 of the Fused Crust from the Kunashak Meteorite

(Note: I - intensity of lines; dα/n and dβ/n - the inter-plane distances, hkl - the indices of the reflecting planes; a is the size of the edge of the units cell.)

Ordinal No. of the line of the Debye powder pattern

Debye powder pattern				Olivine			Enstatite		Magnetite				Kamacite			
	I	dα/n	dβ/n	I	dα/n	hkl	I	dα/n	I	dα/n	hkl	a	I	dα/n	hkl	a
23	1	(2,220)	2,013													
24	6	·2,157	1,955	5	2,165	220										
25	5w*	2,076	1,882				8	2,103	7	2,008						
26	1	2,065	1,872													
27	10	2,017	1,828	2	2,032	221; 132	7	1,960					10	2,032	110	2,842*
28	1	1,941	1,759	7	1,931	240β; 222β										
29	4	(1,924)	1,744	3	1,877	150			2	(1,884)						
30	2	1,881	1,705	2	1,812	142										
31	3	1,810	1,640	2	1,788	151			4	(1,785)						
32	3	1,788	1,620				7	1,780								
33	10	1,749	1,585	10	1,747	240; 222	5	1,731	5	1,710	422	8,392	1	(1,585)	200β	2,884*
34	2	1,713	1,553				5	1,702								
35	1	1,692	1,533													
36	4	1,672	1,516	5	1,671	241										
37	3w	(1,639)	1,485	6	1,639	061; 232			2	(1,632)	440β	8,401				
38	4	1,619	1,467	6	1,619	133	7	1,604	9	1,612	333; 511	8,412				
39	1	1,591	1,442	2	1,588	152?										
40	2w	1,572	1,425	4	1,572	310; 043										
41	1	1,528	1,385	3	1,539	301	7	1,519								
42	2	1,513	1,372	2	1,515	213										
43	8	1,498	1,358	8	1,498	004	9	1,485								
44	8	1,481	1,342	9	1,481	062	8	1,470	9	1,479	440	8,378				
45	2w	1,435	1,300	2	1,437	330; 024							4	1,435	200	2,870
46	6	1,398	1,267	9	1,397 }	312; 233			2	(1,411)						
47	1	1,389	1,259	7	1,387 }		8	1,390								

Table 1 (Continued)

Table 1 (Continued)

No. of line (Debye powder pattern)	I	da/n	$d\beta/n$	Olivine I	Olivine da/n	Olivine hkl	Enstatite I	Enstatite da/n	Magnetite I	Magnetite da/n	Magnetite hkl	Magnetite a	Kamacite I	Kamacite da/n	Kamacite hkl	Kamacite a
48	7	1,351	1,224	9	1,350	322										
49	6	1,316	1,193	9	1,316	134; 243			3	1,325						
50	1	1,299	1,177	3	1,295	044	7	1,305								
51	1	(1,289)	1,168				7	1,292					3	(1,289)	211β	2,860 *
52	1	1,268	1,150	2	1,267	214; 262	8	1,265	5	1,277						
53	1	1,261	1,143	3	1,256				2	1,264	622	8,364				
54	1	1,244	1,127	3	1,238	303		1,250								
55	1	1,227	1,112	3	1,226											
56	1d*	(1,214)	1,100	1	1,209	351; 253	5	1,207	3	1,209	444	8,410				
57	4	1,188	1,077	7	1,188	400			1	1,174						
58	8w**	1,166	1,057	7	1,167	333; 025							10	1,170	211	2,856
59	1	1,157	1,049	3	1,157	420			1	1,153	800β	8,392				
60	2w	1,139	1,034	7; 7	1,140; 1,135	421										
61	1	(1,129)	1,023	5	1,125	064; 430										
62	1	(1,118)	1,013	5	1,117	343			4	1,119	642	8,366	2	(1,118)	220β	2,865
63	1	1,109	1,005.													
64	4w	1,101	0,997	8	1,098	412; 135			8	1,091						
65	3w	1,080	0,979	7	1,080	422										
66	3	1,067	0,967	7	1,074	440										
67	1	1,053	0,955	4	1,052	353	8	1,048	6	1,047						
68	6w	1,040	0,943													
69	4w	1,024	0,928													
70	4w	1,013	0,918										7	1,014	220	2,865 *

$a_{cp} = 8,388$ kX $\qquad a_{cp} = 2,866$ kX

* d - diffuse line
** w - wide line

Ordinal No. of the line of the Debye powder pattern	I	da/n	dβ/n	Olivine			Enstatite		Magnetite				Kamacite			
				I	da/n	hkl	I	da/n	I	da/n	hkl	a	I	da/n	hkl	a
1	1	5,122	4,642	4	5,07	020										
2	1	4,382	3,972	2	4,29	110?			1	4,21						
3	1	4,035	3,657	1	4,04	101β?										
4	6	3,906	3,54t	7	3,87	021										
5	1d*	3,757	3,405	4	3,871	101?	7	3,50								
6	5	3,512	3,183	6	3,491	111	7	3,31	3	(3,31)						
7	1d	3,320	3,009	3	3,333	030	10	3,17								
8	2	3,184	2,886	4	(3,058)	130β										
9	1	(3,077)	2,789	5	2,995	002	9	2,883	6	2,99						
10	2	2,996	2,715													
11	3d	2,864	2,596	9	2,770	130	6	2,700	5	(2,807)	311β	8,366				
12	10	2,783	2,522	3	2,715	112β										
13	1	(2,721)	2,466													
14	1	2,650	2,402													
15	10w**	2,523	2,355	10	2,515	131	9	2,539	10	2,541	311	8,369				
16	10	2,508	2,287	10	2,455	112	9	2,483								
17	1w	2,470	2,239													
18	1w	2,417	2,191	2	2,350	041			3	2,428	222	8,373				
19	1	2,370	2,148	1	2,316	210			3	(2,310)						
20		2,330	2,112													

*d – diffuse line.

**w – wide line.

Table 2. An Interpretation of the Composition of Sample 2 of the Fused Crust from the Kunashak Meteorite

Ordinal No. of the line of the Debye powder pattern	I	dα/n	dβ/n	Olivine			Enstatite		Magnetite				Kamacite			
				I	dα/n	hkl	I	dα/n	I	dα/n	hkl	a	I	dα/n	hkl	a*
21	7	2,271	2,059	9	2,253	122?; 140							4	(2,245)		
22	4 w	2,170	1,967	5	2,165	220										
23	4 w	2,086	1,894													
24	6	2,027	1,837	2	2,032	221; 132	8	2,103	7	2,098			10	2,032	110	2,866
25	1 w	(1,929)	1,749	7	(1,931)	240β; 222β	7	1,960	2	(1,884)	422β	8,406				
26	1 w	1,893	1,716	3	1,877	150			4	(1,785)						
27	1 w	1,851	1,678													
28	1 w	1,794	1,626	2	1,788	142; 151	7	1,780								
29	10	1,758	1,593	10	1,747	240; 222	5	1,731	5	1,710						
30	1 w	1,680	1,522	5	1,671	241	5	1,702								
31	1	(1,647)	1,493	6	1,639	} 232; 061			2	1,632						
32	1	1,630	1,477	6	1,619											
33	1	1,605	1,455	2	1,588	300?; 152?	7	1,604	9	1,612						
34	1	1,578	1,430	4	1,572	310; 043										
35	6	1,502	1,361	8	1,498	004	7	1,519	9	1,479	440	8,412	1	(1,585)	200β	2,860
36	6	1,487	1,348	9	1,481	062	9	1,485	2	(1,411)			4	1,435	200	2,880
37	1 w	1,440	1,305	2	1,437	330; 024	8	1,470								
38	6	1,402	1,271	9	1,397	233; 312	8	1,390	3	1,325						
39	7	1,353	1,226	9	1,350	322			5	1,277						
40	6	1,319	1,196	9	1,316	134; 243	7	1,305					3	(1,289)	211β	2,880
41	1 w	1,287	1,176	3	1,295	044	7	1,292								

Table 2 (Continued)

Ordinal No. of the line of the Debye Powder pattern	I	$d\alpha/n$	$d\beta/n$	Olivine			Enstatite		Magnetite				Kamacite			
				I	$d\alpha/n$	hkl	I	$d\alpha/n$	I	$d\alpha/n$	hkl	a	I	$d\alpha/n$	hkl	a
42	1 w	1,267	1,148	2	1,267	214; 262	8	1,265	2	1,264	622	8,404				
				3	1,256		4	1,250								
43	1 w	1,229	1,114	3	1,238	351; 253										
				3	1,226											
44	2 w	1,192	1,080	7	1,188	400	5	1,207	3	(1,209)						
45	6 w	1,170	1,060	7	1,167	333; 025			1	1,174	800 β	8,400	10	1,170	211	2,866
46	1 d	1,158	1,050	3	1,157	420			1	(1,153)						
47	2 w	1,139	1,032	7	1,140	421										
				7	1,135											
48	1 w	1,119	1,014	5	1,125	343			4	1,119	642	8,374	2	(1,118)	220 β	2,868
				5	1,117											
49	2 w	1,102	0,999	8	1,098	412; 135										
50	1 w	1,081	0,980	7	1,080	422	7	1,080	8	1,091						
				7	1,074											
51	1 w	1,060	0,962	7	1,063	353										
				4	1,052											
52	6 w	1,043	0,945				8	1,048	6	1,047						
53	1 w	1,025	0,929													
54	1	1,013	0,918										7	1,014	220	— 2,865

$a_{cp} = 8,388$ kX $a_{cp} = 2,869$ kX

*

Table 2 (Continued)

* = Not solved

interpretation of the composition of the samples from the fused crust of the Kunashak meteorite is given in Tables 1 and 2. The intensity is given in the second columns and the inter-plane distances for the lines of Debye powder patterns from the meteorite are given in the third and fourth columns.

The fifth, sixth, eighth, ninth, tenth, eleventh, fourteenth, and fifteenth columns contain data on the intensities of lines and inter-plane distances for olivine, enstatites, magnetites, and kamacites respectively.[1]

The seventh, twelfth, and sixteenth columns contain symbols for the structure of olivines, magnetites, and kamacites respectively.

The thirteenth and seventeenth columns give the computed values for a - the edge of a cubical cell for oxymagnetites and kamacites.

In spite of the fact that the samples showed identical mineralogical composition of the fused crust when interpreted, they did show divergences in inter-plane distances and in intensity. This is explained by errors in analysis and possibly by variation in the percentage composition of the minerals composing the fused crust of the Kunashak meteorite. This latter factor was confirmed by mineralogical studies by I. A. Yudin (Ref. 20).

Interpretation of the composition of the crystalline phase of the fused crust indicated that its principal constituent is olivine.

V. I. Mikheyev and A. I. Kalinin (Ref. 12) established a linear dependence of the value of the inter-plane distance for the 004 line on the forsterite - fayalite content, which permitted us to determine the content of the fayalite constituent in olivine (molecule percent). According to the Mikheyev diagram (Ref. 12), and with a value of the inter-plane distance for the line $\frac{d}{n}$ 004 = 1.498 kX, the content of the faya-lite constituent in our samples was 20 molecule percent (for sample No. 1) and the chemical composition of the olivine in this sample of the fused crust of the Kunashak meteorite can be expressed by the formula

$$(Mg_{0.80}Fe_{0.20})_2 SiO_4.$$

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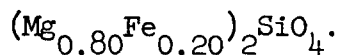
[1] Standard Debye powder patterns for olivine, enstatite and magnetite were taken from the work by V. I. Mikheyev (Refs. 11, 12); the standard Debye powder pattern for kamacite was taken from the work by N. N. Stulov (Ref. 16).

For sample No. 2 in which the inter-plane distance $\frac{d}{n}$ 004 = 1.502, the content of the fayalite constituent was approximately 33 molecule percent, according to the same diagram (Ref. 12), and the chemical composition of the olivine in the second sample can correspondingly be expressed by the formula

$$(Mg_{0.66}Fe''_{0.33})_2SiO_4.$$
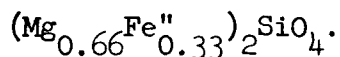
A comparison of the inter-plane distances and intensities of lines for the olivine in our samples with the inter-plane distances and intensities given in the article by E. N. Yeliseyev (Ref. 1) for olivines with a content of the fayalite constituent of 20 and 33 molecule percent shows coincidence in general, which confirms the correctness of the determination of the fayalite constituent in the olivine in our samples. Small deviations in the third place following the decimal point lie within the limits of experimental accuracy and may be caused in part by the multi-component crystalline phase of the fused crust of the Kunashak meteorite.

We find by the diagram (Ref. 1) of the dependence of the specific gravity of the olivine in the fused crust that the specific gravity of the olivine in the fused crust is 3.5 (for sample 1) and 3.6 (for sample 2).

According to data of A. N. Winchell and G. Winchell (Ref. 24) and E. N. Yeliseyev (Ref. 1), olivine with a content of the fayalite constituent of 20 molecule percent has the following indices of refraction: N_g = 1.712, N_m = 1.692, and N_p = 1.674; birefringence is equal to N_g-N_p = 0.038, the angle of the optical axes is equal to 2V = 87°; for olivine with a content of 33 molecule percent N_g = 1.736, N_m = 1.722, and N_p = 1.695; birefringence is equal to N_g - N_p = 0.041; the angle of the optical axes is equal to 2V = 83°.

We computed the length of the a and c sides as it was done in the works of V. I. Mikheyev, N. N. Stulov (Ref. 10), and E. N. Yeliseyev (Ref. 1) on the 004, 400, 140, 240, and 243 reflections. The length of the b axis was determined by solving a system of equations for which we used the inter-plane distances 131, 151 (lines 16 and 32 of the first sample) and 130, 140 (lines 12 and 21 of the second sample).

The following sizes of the unit cell were obtained for olivines from the fused crust of the Kunashak meteorite:

$a = 4.75 \pm 0.01$ kX, $\quad$ b = 10.34 ± 0.02 kX, $\quad$ c = 5.99 ± 0.01 kX (for the first sample);

$a = 4.79 \pm 0.02$ kX, $\quad$ b = 10.39 ± 0.02 kX, $\quad$ c = 6.01 ± 0.01 kX (for the second sample).

It is well known that when the chemical composition of olivine is changed the size of the unit cell also changes (Refs. 1, 10, 12).

An increase in the dimensions of the unit cell of clivine is connected with the replacement of divalent magnesium, which has a smaller ionic radius, with bivalent iron with a larger ionic radius.

The fused crust of the Kunashak meteorite contains less enstatite than olivine. I. A. Yudin found it had an index of refraction N_m = 1.654 and birefringence $N_g - N_p = 0.009$ (Ref. 21).

According to the diagram of A. N. Winchell and G. Winchell (Ref. 24), with an index of refraction $N_m = 1.654$, the content of the ferro-silicate constituent in the enstatite of the fused crust of the Kunashak meteorite was approximately 1 molecule percent, and the chemical composition of the enstatite of the fused crust can be expressed by the formula

$$(Mg_{0.99}Fe_{0.01}) \; (SiO_3).$$
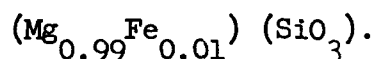
It is possible to determine all optical indices by the diagram (Ref. 24) of the dependence of the optical indices on the enstatite - ferrosilicate. Enstatite with a content of the ferrosilicate constituent of 1 molecule percent has the following indices of refraction: $N_g = 1.661$, $N_m = 1.654$, and $N_p = 1.652$; the birefringence is equal to $N_g - N_p \approx 0.009$? (< 0.010); the angle of the optical axes is equal to $2V = +58°$.

The specific gravity of enstatite (Ref. 24) with these indices of refraction and with a content of 1 molecule percent of the ferrosilicate constituent is equal to 3.15 - 3.20.

A comparison of the Debye powder patterns indicates that the enstatite content of the first sample is somewhat larger than that of the second sample.

The samples contained oxymagnetite and kamacite in far smaller quantities than olivine and enstatite.

Not all the lines of oxymagnetite were indexed. This is explained by the superposition of stronger lines of olivine and enstatite which constituted the basic mass of the samples.

The lines which were indexed were utilized for computing the size of the edge of the cubic cell of oxymagnetite.

The average value of the edge of the unit cell for this mineral was the same in both samples and equal to a = 8.384 kX, somewhat lower than for magnetite with a normal composition $Fe''Fe'''_2O_4$ in which a =

8.396 kX.

As shown by V. I. Mikheyev (Ref. 9), this reduction in the dimensions of the unit cell of magnetite from the fused crust of the Kunashak meteorite is connected with the replacement of a part of the divalent iron, with an ionic radius of 0.79 Angstrom units, in the tetrahedral magnetite structure with trivalent iron with an ionic radius of 0.67 Angstrom units. The value of the edge of the unit cell is a function of the radii of the cations.

As is well known, the formula of oxymagnetite can be represented as follows:

$$(Fe''_{1-x} Fe'''_{2/3x})Fe'''_2O_4,$$
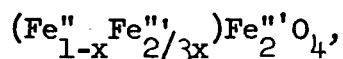
where x is the number of cations of divalent iron in the tetrahedral positions of the spinel structure replaced by trivalent cations.

The number x can be determined for the discovered value of the side of the unit cell a = 8.388 kX by the Mikheyev diagram (Ref. 9) which expresses the dependence of the side of the unit cell of spinellides on the composition. In our case x = 0.10.

Thus, the formula for oxymagnetite acquires the following form:

$$(Fe''_{0.90} Fe'''_{0.07})Fe'''_2O_4.$$
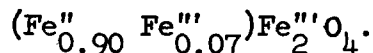
All the kamacite lines (sample No. 1) were indexed in a completely satisfactory manner and the symbols of the reflecting plane lattice of the iron structure are given in column 16. The size of the unit cell was computed in accordance with them and turned out to be equal to a = 2.866 kX.

According to the diagram of the dependence of the size of the edge of the iron unit cell on the nickel content (Ref. 12), we find that with our value of the size of the unit cell the nickel content in the kamacite is equal to not less than 6 atom percent.

All the kamacite lines, except line No. 21, were indexed for the second sample and the size of the unit cell, which turned out to be equal to a = 2.869 kX, was computed by the symbols of the reflecting plane lattice as given in column 16.

As shown in the articles by V. I. Nikheyev (Ref. 12) and N. N. Stulov (Ref. 16), the increase in the parameter in the k: :ites is connected with an increase in the nickel content. Thus, the nickel content in the kamacite of the second sample is somewhat higher than that in the first sample.

We noted variation in the nickel content in kamacite from the same meteorite previously when studying the Nikol'skoye meteorite (Ref. 4).

Our investigations do not exclude the presence of taenite (all lines of the standard Debye powder pattern for taenite were superimposed on the lines of the minerals identified above), but it will be necessary to carry out additional x-ray studies of the nickeliferous iron in the fused crust in order to obtain certain identification of taenite in that crust. I. A. Yudin (Refs. 20, 21) pointed out the presence of taenite in the fused crust of the Kunashak meteorite.

The works of I. A. Yudin (Refs. 20, 21) also note the presence of the mineral IOTSIT in the fused crust of the Kunashak meteorite, but in view of the superposition of the IOTSIT lines on the lines of the minerals identified above, its accurate determination has been made difficult.

On the remaining six unsolved lines (first sample) line 69 with an intensity of 4 and line 14 with an intensity of 2 are of the greatest interest. The other four lines (Nos. 15, 26, 35, and 63) have the lowest intensity number 1.

The inter-plane distances of the majority of the unsolved lines of the first sample are close to the inter-plane distances of the unsolved lines of the second sample (deviations from 0.001 to 0.013). This indicates that the lines in the two samples are associated with the same mineral which we did not succeed in identifying.

The results obtained from previous investigations (Refs. 2, 5, 8, and others) permitted us to represent three variants of the formation of

oxymagnetite in the fused crust of stone meteorites.

Element	Content		Element	Content		Element	Content
Si	1-10		Al	1-10		Mg	> 10
Ca	0.1-1		Fe	> 10		Mn	~ 0.1
Ni	0.1-0.3		Co	0.01-0.03		Ti	0.001-0.01
V	0.001?		Cr	0.03-0.1		Cu	0.03-0.1
Pb	< 0.001		Ag	Traces		Zn	0.05-0.1
Sn	Insignif-icant traces		Ge	0.003		Na	~ 1

Table 3. Content of Different Elements in the Fused Crust (Percent)

The first variant is the process of conversion of meteoritic iron into oxymagnetite which can be schematically represented:

$$Fe \longrightarrow FeO \longrightarrow Fe''_{1-x}Fe'''_{2/3x}O \longrightarrow Fe''Fe'''_2O_4 \longrightarrow (Fe''_{1-x}Fe'''_{2/3x})Fe'''_2O_4$$

meteor-itic iron	ferrous oxide	IOTSIT	magnetite	oxymagnetite
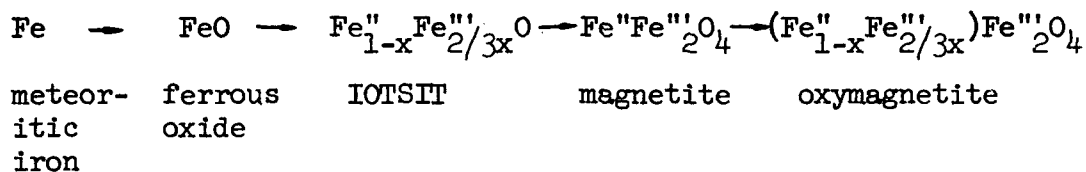
This process is analogous to the process of conversion of meteoritic iron into oxymagnetite in the fused crust of iron meteorites suggested by V. D. Kolomenskiy in 1956.

According to Mikheyev's suggestion, nickel is present in the fused crusts of iron and stone meteorites in the form of an isomorphous admixture.

The second variant, the formation of oxymagnetite from troilite:

$$FeS \longrightarrow FeO \longrightarrow Fe''_{1-x}Fe'''_{2/3x}O \longrightarrow Fe''Fe_2'''O_4 \longrightarrow (Fe''_{1-x}Fe'''_{2/3x})Fe_2O_4$$

troil-ite	ferrous oxide	IOTSIT	magnetite	oxymagnetite
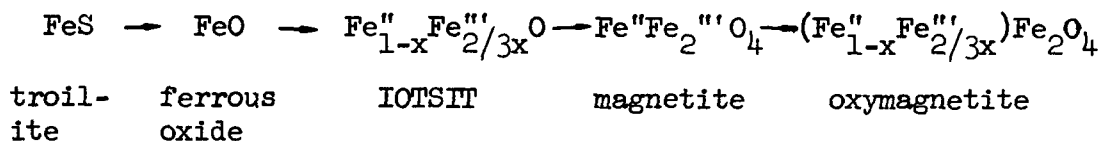
The sulfur dioxide which forms in the oxidation of troilite escapes. This variant of gradual conversion of troilite into oxymagnetite may

also occur in the fused crusts of iron meteorites.

The third variant, the formation of oxymagnetite in the fused crust from magnetite (the presence of magnetite in stone meteorites indicates this possibility (Refs. 2, 8)):

$$Fe''Fe'''_2O_4 \longrightarrow (Fe''_{1-x}Fe'''_{2/3x})Fe'''_2O_4.$$

magnetite   oxymagnetite
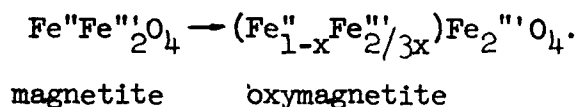
Thus oxymagnetite in the fused crust of stone meteorites can be formed from meteoritic iron as well as from magnetite and troilite.

Oxymagnetite from a fused crust is an intermediate member of the magnetite $Fe''Fe'''_2O_4$ - γ maghemite - Fe_2O_3 series and if maghemite is

present in the fused crust of stone and iron meteorites, then the above mentioned process can be continued from oxymagnetite to maghemite

$$(Fe''_{1-x}Fe'''_{2/3x})Fe'''_2O_4 \longrightarrow \gamma - Fe'''_2O_3.$$
$$x = 1$$

oxymagnetite   maghemite
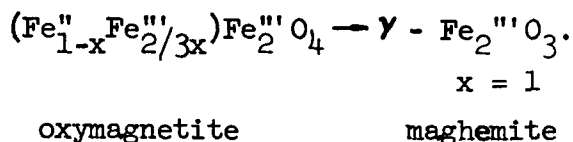
Hydrogeothite and hydrohematite are formed in the fused crusts of meteorites under terrestrial conditions (Ref. 16).

Our investigations have been confirmed by experimental data. IOTSIT was synthesized by I. A. Yudin (Ref. 5). He mixed bits of nickeliferous iron in an iron pipe sealed on both ends by iron plugs. This

mixture was held for 29 hours at a temperature of $1,000^{\circ}$ in a muffle furnace. IOTSIT was obtained on the edges of the nickeliferous iron as a result of the experiment he conducted.

Oxymagnetite was obtained in the X-Ray Laboratory of the Leningrad Mining Institute by E. P. Sal'dau (Ref. 13) who roasted magnetite with free access to air. E. P. Sal'dau established a regular variation (increase) in the size of the unit cell of magnetite in accordance with the degree of oxidation of divalent iron.

With further heating oxymagnetite is converted into maghemite, then into hematite (Refs. 13, 14, 15).

V. V. Khokhlov carried out a semi-quantitative spectral analysis of one sample of the fused crust of this meteorite for a more complete study of the fused crust of the Kunashak meteorite, also to determine

small admixtures, in the Spectral Laboratory of the Leningrad Mining Institute. The results are given in Table 3.

On comparing the results obtained from semi-quantitative spectral analyses of the fused crust of the Nikol'skoye (Ref. 23) and Kunashak meteorites, we note certain differences:

a) A number of metals (lead, silver, and zinc) were found in the fused crust of the Kunashak meteorite which were not found in the fused crust of the Nikol'skoye meteorite;

b) A somewhat higher copper content than was found in the fused crust of the Nikol'skoye meteorite.

Conclusions

The data obtained from x-ray analysis showed that the principal mineral in the fused crust of the Kunashak meteorite is lead, olivine being of varying abundance. The olivine content, the size of its unit cell, and its specific gravity were determined in two samples.

In sample 1 the olivine composition corresponded to the formula

$$(Mg_{0.80}Fe''_{0.20})_2 SiO_4.$$
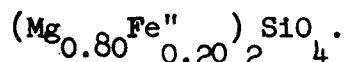
The dimensions of its unit cell were:
a = 4.75 ± 0.01 kX; b = 10.34 ± 0.02 kX; c = 5.99 ± 0.01 kX; specific gravity - 3.5.

In sample 2 the olivine composition corresponded to the formula

$$(Mg_{0.66}Fe''_{0.33})_2 SiO_4.$$
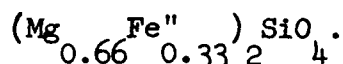
The dimensions of its unit cell were:
a = 4.79 ± 0.02 kX; b = 10.39 ± 0.02 kX; c = 6.01 ± 0.01 kX; specific gravity - 3.6.

Enstatite is encountered in smaller quantitites, being a little higher in the first sample. The content of the ferrosilicate constituent in the enstatite was ~ 1 molecule percent; that is, it corresponds to the formula

$$(Mg_{0.99}Fe_{0.01})SiO_3.$$
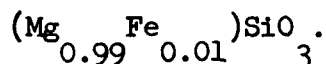
The specific gravity of the enstatite was 3.15 - 3.20.

Oxymagnetite and kamacite are contained in far smaller amounts than olivine and enstatite.

The oxymagnetite in the fused crust of the Kunashak meteorite corresponds to the formula

$$(Fe''_{0.90}Fe'''_{0.07})Fe'''_2O_4.$$
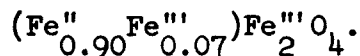
The average value of the edge of the oxymagnetite unit cell is $a = 8.388$ kX (somewhat lower than for magnetite for normal composition, in which $a = 8.396$ kX).

The average value of the edge of the unit cell of the kamacite in the fused crust of the Kunashak meteorite was found to be:

$a = 2.866$ kX (in the first sample),

$a = 2.869$ kX (in the second sample).

It corresponds to a nickel content of not less than 6 atom percent. The difference in the parameters is obviously connected with variation in the nickel content in the kamacite. The nickel content was higher in the second sample.

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VI. DETERMINATION OF THE LEAD CONTENT IN IRON METEORITES

by   I. Ye. Starik, E. V. Sobotovich,
and G. P. Lovtsyus

Russian Text Pages 100-102.

The lead content in iron meteorites has been determined by many investigators. The results obtained vary over very wide limits from $n \cdot 10^{-5}$ to $n \cdot 10^{-7}$ g/g which apparently can be explained by possible contamination by terrestrial lead and by the presence of irregular troilite inclusions in the metallic phase.

The results obtained for some iron meteorites are presented in this article. We applied a new method for separating lead which will eliminate to a considerable extent the shortcomings of the usual chemical methods. It consists essentially of chemical decomposition of the sample with subsequent pyrochemical separation of the lead.

We described the apparatus and the principles of the method of pyrochemical analysis previously (Ref. 1). The analysis was conducted with a radioactive control, the radioactive indicator ThB being introduced into a nitric acid solution of the iron meteorite. The lead was separated out of the dry Fe_2O_3 residue by an ordinary pyrochemical method in a stream of hydrogen at 1200°. Control experiments showed that contamination by foreign lead from reagents, laboratory ware, etc., amounted to $1\text{-}2 \cdot 10^{-6}$ grams in processing 150 grams of meteorite.

The table contains experimental data on the quantitative determination of lead in three iron meteorites with different zones of individual fragments of the Sikhote-Alin' and Chinge, also troilite inclusions being subjected to analysis.

As may be seen from the table, the lead content in the Sikhote-Alin' meteorite decreases with distance from the fused crust (samples 2, 3, and 4). It is possible that the surface zone of this sample has been contaminated to a considerable degree with lead of terrestrial origin. It should be noted that the 6 kg sample of the Sikhote-Alin' which was placed at our disposal was heavily intersected with crevices and fracture which could have accumulated lead of terrestrial origin. This is indicated by the increased lead content in sample 1, which was an uncleaned piece of the meteorite. A similar contamination of the peripheral parts was also observed in the Chinge meteorite, the lead content in the peripheral part (sample 6) was equal to the lead concentration in

Sample*	Batch, Grams	Content 10^{-6} g/g	Sample*	Batch, Grams	Content 10^{-6} g/g
	Sikhote-Alin'			Chinge	
1	34.5	1.4	4	25.0	0.25
	18.4	1.2		24.0	0.14
2	16.4	0.54		17.0	0.14
	36.7	0.49	5	40.3	0.021
3	19.2	0.23			
	15.2	0.25		100.0	0.027
	45.3	0.25		Henbury	
	35.3	0.26			
	28.8	0.27	6	17.2	0.26
				24.1	0.46
				100.2	0.28
				Troilite from Sikhote-Alin' meteorite	
			7	1.20	1.2
				0.87	0.9
				Henbury Troilite	
			8	3.26	5.0

* The samples represent different zones and troilite inclusions from individual specimens of meteorites: 1, 4 are filings from a meteorite without careful cleaning; 1 is a carefully selected shaving from the fused crust (with no troilite inclusions); 2, 4 are shavings at a depth of 5-10 mm (with no troilite inclusions); 3, 5 is a carefully selected shaving from a depth of 15-20 mm (without troilite); 6 is a shaving from a depth of 15-25 mm (troilite inclusions possible); 7, 8 — carefully selected troilite.

THE LEAD CONTENT IN CERTAIN IRON METEORITES, IN DIFFERENT ZONES OF THESE METEORITES, AND IN TROILITES

the central parts of the Sikhote-Alin' and Henbury meteorites (samples 4 and 8), while the lead content in the central part of the metallic phase of the Chinge meteorite was one order lower and amounted, on the average, to $2.4 \cdot 10^{-8}$ g/g (sample 7). This was the first time that such a small lead content had been noted in the metallic phase of an iron meteorite. The individual sample of the Chinge meteorite was a very

dense and compact fragment weighing about 5 kg, with an egg-shaped form. No visible destruction or inclusions were observed in the cuts.

The sample from the Henbury meteorite was also a well preserved fragment with a weight of 4.2 kg; however, it was heavily veined with troilite. It is possible that this explains some deviations in the values of the lead content for three parallel analyses of the metallic phase of this meteorite (sample 8), with the higher value of the lead

content, namely $4 \cdot 10^{-7}$ g/g, coinciding with the results of Patterson's analysis of this meteorite (Ref. 2).

In the light of the research which has been conducted, the values we obtained previously for the lead content in the Sikhote-Alin' and Chinge meteorites (refer to samples 1, 5) (Ref. 3) can be considered high, which is apparently explained both by contamination with foreign lead and by the presence of possible troilite inclusions in the pieces of meteorites which were analyzed.

It was of considerable interest to determine the lead concentration in the troilite separated out of the Sikhote-Alin' and Henbury meteorites. As we have stated previously, we found no troilite inclusions in the sample of the Chinge meteorite.

The troilite inclusion in the Henbury meteorite had the form of a sphere with a diameter of 12 mm. Its lead content turned out to be

$5.0 \cdot 10^{-6}$ g/g, which agrees completely with Patterson's data for this troilite. The lead concentration in the troilite from the Sikhote-Alin'

meteorite was $1 \cdot 10^{-6}$ g/g (sample 9).

Thus, the research which has been done shows that the surface parts of the fragments from the Sikhote-Alin' and Chinge meteorites have been contaminated to a considerable degree with foreign lead, apparently of terrestrial origin. The probability that the true cosmic lead content in iron meteorites could turn out to be considerably less is not ruled out.

If we assume that iron meteorites are formations with the same genesis, then we apparently should consider that the true lead content

in the metallic phase of meteorites should not exceed $2 \cdot 10^{-8}$ g/g (sample 7). It is possible that the higher values for lead concentration which we and other investigators obtained can be explained by contamination with lead of terrestrial origin and also by the presence of troilite inclusions which are difficult to separate.

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VII. PRELIMINARY RESULTS OF THE WORK OF THE TUNGUS METEORITE EXPEDITION OF 1958

by K. P. Florenskiy, V. I. Vronskiy, Yu. M.
Yemel'yanov, I. T. Zotkin,
and O. A. Kirova

Russian Text Pages 103-134.

The Basis for Works on the Subject. The field work for studying the vicinity of the fall of the Tungus meteorite which was conducted by L. A. Kulik was completed in 1939. The results of these expeditions were set forth in greater detail in the summary by Ye. L. Krinov (Ref. 1), who added his personal observations and data obtained from partial processing of aerial photographs in 1938. I. S. Astapovich gave another summary on all information on the meteorite (Ref. 2). The post-meteoric period was characterized by a relatively small amount of original works in which previously gathered material was reviewed in some manner or another. Of these works one must note the article by Academician V. G. Fesenkov (Ref. 3), who evaluated the amount of material thrown into the atmosphere on the order of 10^6 tons on the basis of the atmospheric turbidity in July 1908, according to data from the actinometrid station on Mt. Wilson, California, which was the only station of its kind at that time, and by connecting this with the Tungus meteorite.

On the basis of an analysis of the few witnesses' statements collected previously by the Committee on Meteorites, N. N. Sytinskaya (Ref. 4) showed that the paths of the meteorite, as determined by Ye. L. Krinov (Ref. 1) and I. S. Astapovich (Ref. 2), were equally probable; that is, they were essentially unreliable.

B. Yu. Levin (Ref. 5) gave an analysis of the probable velocities of the Tungus meteorite and concluded that the meteorite did not necessarily meet the earth head-on, but rather had overtaken the earth, so that its velocity could vary within wide limits. With a parabolic heliocentric velocity, the Astapovich variant of the path corresponds to 12.0 -67.1 km/sec and the Krinov variant to 12.0-46.8 km/sec.

K. P. Stanyukovich (Ref. 6) showed that the vibrations in the ground and in the air, also the destruction on the ground, which had been explained as being due to the explosion of the meteorite when it struck the earth, could also be explained by the action of the ballistic waves from the meteorite without any direct collision of its material with the earth at a cosmic speed.

A review of Whipple's data (Ref. 7) showed that the energy of the Tungus meteorite, which Whipple had estimated at 3.2×10^{20} ergs, should probably be increased to 10^{23} ergs, since losses of energy in heating the air in propagation of the shock wave had not been taken into account.

Thus, all investigations show that the known factual data are wholly inadequate for unique and reliable judgment on the nature of the meteorite, and the acquisition of additional factual material is essential.

We recall that the region in which the meteor fell remained completely unstudied as a whole, the boundaries of the destruction on the ground (felling of trees) were not established and were outlined provisionally on a topographical basis known to be unreliable; no systematic searches were made for the material in the meteorite outside the craters (thermokarst craters), and the aerial photographs included only the central part of the felled forest and remained unprocessed.

At the same time, the known facts were set forth in part of the literature, particularly the popular literature, inaccurately, tendentiously, and simply incorrectly. As a result, the existing hypotheses were considered to be reliable facts or, on the contrary, the entire "Tungus catastrophe" was represented as some inexplicable riddle which would permit any arbitrary proposition if only it were not obviously entirely absurd. The descriptions given by witnesses which were quite contradictory in details and collected 20-25 years after the fall, afforded sufficient scope for such arbitrariness.

Unreliable elucidations of the facts are also encountered in the scientific literature. Thus, the book Mezhdu planetami (Between Planets) (Ref. 9) contained a photograph of the Suslovskaya thermokarst crater which was represented to be the crater made by the explosion of the Tungus meteorite.

A brief visit to the vicinity of the fall made by K. P. Florenskiy in 1953 (Ref. 10) showed that the destruction on the ground by the meteorite remains to this day, and it can be investigated more carefully.

In 1957 A. A. Yavnel', who was studying samples of the soil brought in by L. A. Kulik and K. P. Florenskiy (under the auspices of the Committee on Meteorites) discovered iron particles of meteoritic origin and misroscopic spherules which were obviously magnetite (Ref. 11,12) in these samples. It was suggested that these particles are associated with pulverized residues of the Tungus meteorite. Even though it became clear later that this conclusion is probably premature, it

provided a key to wider searches for similar particles, which gave considerable definiteness to the objectives of the intended expedition.

Thus, the entire history of the study of the Tungus meteorite indicates the necessity for serious replenishment of the factual basis of our knowledge of the meteorite by a comprehensive study of this complex phenomenon by specialists from different branches of natural sciences. It is essential to refrain from hasty and premature conclusions made prior to the acquisition of wholly reliable and sufficiently complete factual material.

The expedition organized by the Committee on Meteorites of the Academy of Sciences, USSR in 1958 started with the following basic propositions in organizing its work.

1. The work done in preceding years (L. A. Kulik) was based on the study of a very small section of the central part of the felled forest. The entire region of the fall has not yet been studied as a whole.

2. The fall of the Tungus meteorite should have been followed by very heavy scattering of finely dispersed material and the probability of finding such material far exceeds the probability of finding large pieces of the meteorite, which were the object of searches in preceding work.

3. The meteorite was essentially an iron meteorite and particles of meteoritic iron have been preserved in the soil up to the present time in an unoxidized state.

The Objectives and Composition of the Expedition. In view of the short time available for work, the expedition was to be of a reconnaissance nature with the following concrete objectives:

1. To make traverses of the region of the forest felled in 1908 and establish the general nature of the felled area and its boundaries, mapping them on a modern topographical background obtained by aerogeodetic means.

2. To collect samples of the soil and concentrate them in the field to a magnetic concentrate. These concentrates should be analyzed by mineralogical and chemical means with determination of the Ni : Fe ratio in order to obtain isolines of the content of these metals and further conclusions on places of concentration of particles from the meteorite. A portion of the samples were to be in duplicate for detailed processing in Moscow. The samples were to be taken over a grid with sides of about five kilometers.

3. To make a general evaluation of the region of the fall of the meteorite with the aim of clarifying objectives and prospects for further work.

The organization of this expedition was entrusted to a co-worker of the Vernadskiy Institute of Geochemistry and Analytical Chemistry, Geochemist K. P. Florenskiy. The expedition included Mineralogist O. A. Kirov (Aleshkov), Geologist B. I. Vronskiy, Chemist Yu. M. Yemel'yanov, Astronomer I. T. Zotkin, Physicist S. A. Kuchay, Chemist P. N. Paley, Laboratory Assistants of the KMET (Committee on Meteorites) Ye. I. Malinkin and T. M. Gorunova, and K. D. Yankovskiy, who participated in the 1929-1930 Expedition and who could evaluate changes which had taken place in the region in 28 years.

The expedition was guided by senior guides, the Evenki A. I. Dzhenkoul' and A. I. Doonov. A movie cameraman from the Moscow Studio of Popular Science Films, M. A. Zaplatin, was attached to the expedition.

The expedition took a train to Krasnoyarsk, went by plane to Vanavary (with a landing at Kezhma), then by reindeer caravan to the base which consisted of Kulik's huts. The expedition was organized in three sections; two of them made traverses, supported by a base in which field mineralogical and chemical studies of the collected samples were conducted. All transverses from the base were made on foot.

The expedition left Moscow on 3 June and returned on 10 August having spent 34 days on the site of their work.

The methods for conducting the work and the preliminary results obtained by the Tungus Meteorite Expedition of 1958 are presented below.

Destruction of the Forest. The felling of the forest still remains the chief indication of the fall of the meteorite in this region, therefore, it is essential to discuss its characteristics in detail.

The total area of the felled forest occupies about 1,500 square kilometers and is separated sharply from the windfalls observed in this region by its orderliness and scale (Figure 1). A diagram of the traverses along which observations were made is given in Figure 2. The measured azimuths of the fallen trees are shown on the map (refer to Figure 1) in the form of arrows whose bases correspond to the points of observation. Each arrow corresponds to the dominant direction of the fallen trees over a considerable area and is plotted with an accuracy of about 5 degrees. The fallen trees lie, in general, in parallel rows, but accurate measurements in a level place show deviations on the order of this magnitude which probably depend on the shape of the crowns, the arrangement of the root systems, and other individual peculiarities of
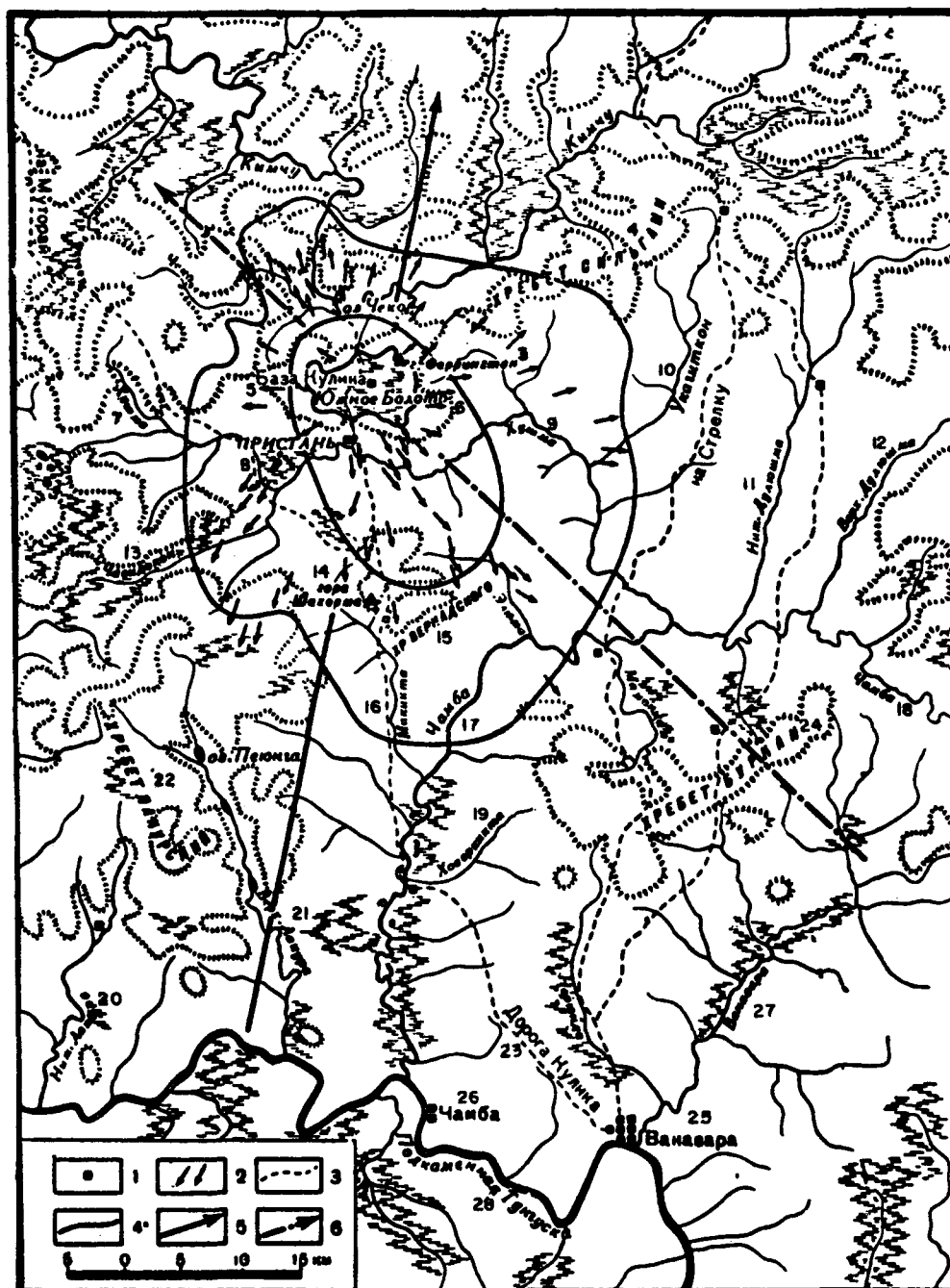
Figure 1. Region of the work of the Tungus meteorite expedition of 1958. The direction of fallen trees, the boundaries of felling of the forest of different intensity and variants in projections of the path.

1- huts; 2- felling of trees; 3- trails; 4- boundaries of zones of damage; 5- path according to Astapovich; 6- path according to Krinov. See page 140 for transliteration of place names.

the trees which cannot be taken into account.[1]

This investigation by traverses completely confirmed the general radial character of the felling of the forest over a large area which has been established by Kulik for the central and southern parts of the region. However, the discovery of several local centers of felling which lay about the southern bog, which L. A. Kulik tried to separate (refer to (Ref. 1), page 146 and Figure 35) was scarcely of an objective character and requires more careful study of local conditions.

Figure 2. Diagram of trips made by the expedition and points at which soil samples were taken.

The effect of the relief on the direction of felling was noted by

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[1] The arrow to the west of South Bog marks a case of anti-parallel felling in which treetops were turned in opposite directions; the point of observation corresponds to the middle of the arrow.

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Legend to Figure 1.

1.	Kimchu	15.	Vernadskiy Range
2.	Lake Cheko	16.	Makikta
3.	Mt. Farrington	17.	Chamba
4.	Sil'gami Range	18.	Chamba
5.	Kulik's Base	19.	Khovorkikta
6.	South Bog	20.	Lower Lakura
7.	Khushma	21.	Upper Lakura
8.	Pristan'	22.	Lakyrsniy Range
9.	Khushma	23.	Kulik's Route
10.	Ukagitkon	24.	Burkan Range
11.	Lower Dulyushma	25.	Vanavara
12.	Upper Dulyushma	26.	Chamba
13.	Chavidokon	27.	Vanavara
14.	Mt. Shakhorma	28.	Podkamenskaya Tunguska

Legend to Figure 2.

1. Lake Cheko
2. Kulik's Base
3. Kimchu
4. Sil'gami Range
5. Farrington
6. Pristan'
7. Khushma
8. Chavidokon
9. Shakhorma
10. Khladnyy Range
11. Vernadskiy Range
12. Makikta
13. Chamba
14. Ukagit
15. Ukagitkon

Transliteration of numbered Russian place names.

Ye. L. Krinov (Ref. 13) and was undoubtedly observed on the site in a number of cases. This is particularly clear in the peripheral parts of the region where the wave was attenuated, although it was also traced in more central areas. Such places which can be noted include the folded relief in the mountains north of the Khushma River to the east of the Churgima and the Upper reaches of the Makikta River where the direction of felling took a direction along the river valley if it formed a small angle with the general direction of felling. This feature was retained for some time when there was a sharp turn in the valley.

At attempt was made in field work to discover the general deviation from the central symmetry in the directions of the fallen trees, but the observations were too few to solve this problem. In view of its importance in a general description of the phenomenon, it should be established by study indoors of the available aerial photographs (scale of 1 : 5000 for the central area and 1 : 50,000 for the peripheral part of the region) and also by subsequent expeditions. At the same time, special attention should be directed to the peripheral parts of the region which lie in the direction of the assumed path of the meteorite.
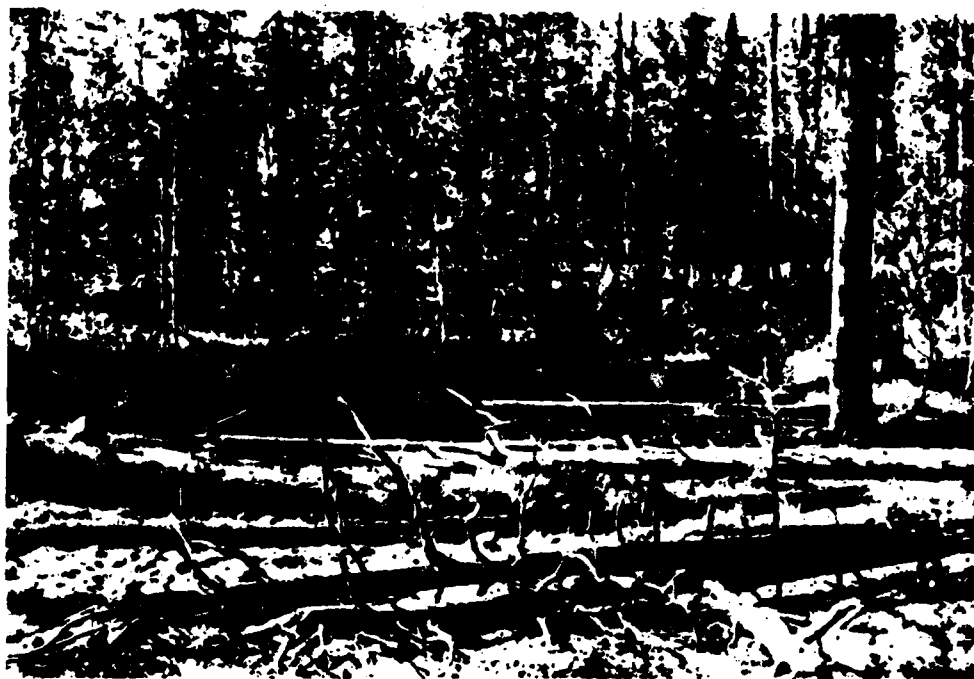
Figure 3. Fallen trees west of South Bog lying among the young forest.

It should be noted that the 50 years which have passed since the meteorite fell have made the study of this phenomenon as a whole a difficult matter. Later fires and windfalls have masked the destruction of 1908 in many places. The remains of the deciduous forest have rotted completely in this time and places of former fir and aspen thickets will

Figure 4. Kulik's hut near Pristan' in 1958.
The forest which has grown up in 20 years is seen here.

Figure 5. Suslov crater in 1958. Birches growing on
the site of a trench dug in 1929 to drain off the
water.

always remain as empty spots in the general picture of felling. As coniferous trees are less subject to rot, they are quite readily observed up to present times, but the growth of a young, already large forest (Figures 3-5) hampers the study to a large degree. Many details which characterize the types of destruction have either disappeared altogether or are observed with great difficulty.

One may distinguish the following types of destruction of the forest:

1) uprooted trees--the prevailing type in the principal area, particularly typical of deciduous trees (Figure 6);

2) trees broken off near the roots without having the crowns broken off (Figure 7);

3) trees like pillars--dried-up trees with crowns broken off in 1908--most typical of pines (Figure 8);

4) bare trunks--trees (at times very large) which have dried up from the roots without any breakage of the trunks, probably due to loss of branches and needles when the meteorite fell, predominantly deciduous trees (Figure 9);

5) dried trees which dried up without loss of branches, possibly because of burning and dessication of needles in fires;

6) partial damage to trees (Figure 10).

The first two types of destruction are apparently connected with the relationship of the force of the shock wave and the strength of the root systems of the trees, which depends on the conditions for growth and the species of the trees. The bounds between the last types are not always clear now and require study of each tree separately since one can observe the natural fall of rotted branches and treetops which have occurred in these 50 years since the catastrophe. The entire phenomenon is now complicated greatly by subsequent windfalls of dead trees.

It seems to us that a study of the statistical distribution of different types of destruction, along with detailed studies which take the biological peculiarities of trees into account, can yield a valuable description of the shock wave, but this is a very laborious task.

Such an attempt was undertaken by I. T. Zotkin and S. A. Kuchay in twelve 0.3-hectare sections between the South Bog and the Khushma River, along the course of the Churgima Creek. This region has several sharp breaks in the relief (Figures 11 and 12) and it was interesting to establish some sort of regular connection between the destruction and the orientation of the slopes with the aim of discovering areas shielded from the action of the shock wave. The data collected require further processing (refer to the Table), but preliminary results indicate that this connection is not sufficiently clearly expressed in the central part of the region which lies close to the projection of the path of the meteorite. It can be seen from the Table that the average percentage of

uprooting was 7 percent on the northern slopes and reached up to 35 percent of the total number of trees on the southern slopes.

Different Types of Damage to Trees[*] Between the South
Bog and the Khushma River Along Churgima Creek

Number of Section	Shielding, Degrees	Inclination, Degrees	Dead Trees per 0.3 Hectares	Uprooted	Bare Pillars		Bare Trees		Broken off near roots	Broken Stump Cause Unknown	Old, Living Trees
					Upright	Fallen	Upright	Fallen			
1	0	+5	199	9	16	12	13	43	2	5	0
2	0	+11	182	2	19	25	5	45	0	4	0
3	29	-17	199	22	4	14	5	53	2	0	0
4	5	+13	130	14	26	22	3	26	6	3	0
5	0	0	149	46	11	2	0	20	19	2	0
6	15	-10	186	37	11	12	3	29	6	2	0
7	11	+6	100	2	17	17	20	42	2	0	0
8	5	0	178	35	7	13	2	32	8	3	0
9	21	-14	204	28	7	6	8	45	6	0	0
10	8	-1	155	51	6	14	2	13	12	2	0
11	4	+16	167	10	2	15	3	49	10	11	0
12	0	-10	360	34	3	13	5	32	8	5	0

[*] Damage given in percent.

The sign + in the Table denotes the inclination of the section toward the north and the sign - the inclination in the opposite direction. The angle between the horizon and the direction to the top of the closest mountain range bounding the given section from the north was called the angle of shielding. The prevailing direction of movement of the shock wave and the direction of the fallen trees was from north to south. The terms standing and fallen are used to denote the percent of bare trunks and pillar-like trees (without branches or tops) which remained upright and died and fell after 1908 respectively.

Boundaries of Felling of the Forest. This investigation was carried out chiefly by K. P. Florenskiy and B. I. Vronskiy, assisted by K. D. Yankovskiy, Yu. M. Yemelyanov, and S. A. Kuchay. The determination of accurate boundaries of felling, like all gradually disappearing phenomena, was not of a wholly objective nature, particularly if one takes a number of complicating factors connected with the passage of the 50 years since the event into account.

Figure 6.   Uprooted tree in the vicinity of Pristan'.

Figure 7.   Tree broken off near the roots.   The picture
was taken on the volcanic cones east of Churgima Creek.

A relationship was noted in peripheral areas between the amount of felling and the relief--felled trees were found on the tops of mountains and in valleys which extended along the direction of action of the shock wave. Individual spots with felled forest were noted on heights far from the boundaries indicated on the attached map (Figures 1 and 13), but it is very difficult to distinguish between trees destroyed by the meteorite and those windfalls that happened to fall in that direction.

Figure 8. Pillars--tree trunks with tops torn off
(in the vicinity of Pristan').

In compiling a schematic map of the felled area, we made use of a forest map on a scale of 1 : 250,000 compiled in 1954 by an aerial survey expedition from the Leningrad LESPROYEKT Trust (Trust for Planning Forest Enterprises) (Figure 14) along with our own observations. This map, which is based on aerial photographs, shows the distribution of forests of different ages. However, it was noted from checking on the site that, in a number of cases, drowned forests in swampy areas were shown on the forest map in incorrect age groups. Moreover, the forest

map shows patches of young forest irrespective of the reasons for their appearance, thus provides only supplementary material, not an exhaustive basis for our work.

It should be emphasized that the schematic map presented here (refer to Figure 13) is the first diagram of the felled forest on an accurate topographical base; all constructions and conclusions connected with the preceding diagrams (Obruchev, Suslov, Kulik, Krinov, Florenskiy) should be reevaluated in respect to the new map, with account being taken of the reservations which have been made here. Considerably more detail can be filled in with subsequent processing of aerial photographs and this map is not yet an accurate basis for quantitative mathematical calculations which would reflect a quantitative description of the phenomenon with sufficient faithfulness.

Figure 9. Bare trunks--dead trees with branches broken off (larches). Region south of South Bog.

We separated the damaged forest into three zones.

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1. We provisionally called the zone where there was no oriented felling of the forest the "neutral zone, or the zone of disorderly felling". It was located in the bounds of a basin about the South Bog and corresponded to the central region from which the oriented radial felling of the forest began. Extensive development of dry stands (Figure 15) in the form of bare trees and pillars (bare trees without branches or treetops) or ("telegraph poles" Kulik) which had fallen to the ground in disorder since 1908, without any definite orientation, depending on local winds, was observed in this zone. This zone was included in the aerial map of 1938 and can be contoured with sufficient accuracy through processing indoors.

Figure 10. Damage to a tree which was characteristic of the zone of partial felling of the forest - the uprooted tree contined to live, growth continued by a lateral branch.
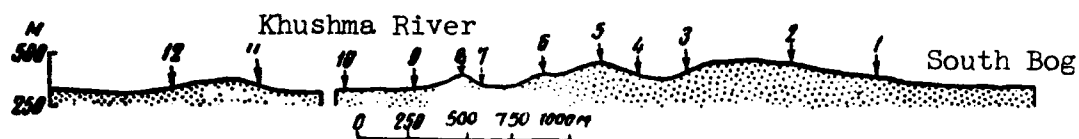
Figure 11. Profile of relief along Churgima Creek. The areas where damaged trees were counted are shown by arrows.

2. The zone of mass felling. We called this zone the "zone of mass radial felling" even though individual groups and thickets of trees and single trees remained within its bounds. One might evaluate its boundaries visually by 80-90 percent fallen trees. The "neutral zone" was located inside the zone of mass felling in a clearly off-center manner, being located in its northern or northwestern part, as was assumed by Ye. L. Krinov. Careful processing of the aerial maps of 1938 and 1949 or additional traverses will be required for final judgment on the shape of the zone of mass felling.

3. A zone of partial felling whose boundaries are the most uncertain. A comparison of the boundaries on the map which we accepted with the boundaries of the felled forest as drawn by hunters who know this region well (A. I. Doonov and A. I. Dzhenkoul'), and also with the boundaries given by Ye. L. Krinov (a visual map for the southern and southeastern parts of the region) and K. P. Florenskiy (by aerial observation and data obtained by questioning) shows the degree of their objectiveness (refer to Figure 13). The discrepancies between these boundaries do not exceed 5 km (usually less) and give an idea of the possible magnitude of the error. The schematic boundary of felling could be made more accurate on the basis of data from aerial photographs. The same thing applies to the discovery of individual sections of old forest which have remained inside this territory. The boundary of partial felling probably corresponds to 15-25 percent felled trees. A complete restoration of the picture of the destruction is scarcely possible now, and would be very laborious in any event since it would be necessary to provide for a complete ground forest map with a large amount of controlled felling in order to establish the age of the trees.

Figure 12. Waterfall on Churgima Creek.

       The Fire in 1908. L. A. Kulik and Ye. L. Krinov (Ref. 1)
pointed out that traces of burns were noted on the majority of the
trees in the central part of the region where the trees were felled.
They observed that these burns were specific in that breaks in both
thick and thin branches were burned, breaks with an angle at the end
were pointed down, reminding one of "birds' claws", and branches on
standing trees were arched downward. This permitted them to draw
conclusions of an instantaneous burning action which was not followed

Figure 13. Diagram of variants of boundaries of damaged forest: according to Ye. L. Krinov (1949, contours changed greatly in connection with improved topographical base), according to K. P. Florenskiy (1953), according to the forest map (1954; sections of forest younger than 40 years), according to information from questions (1958 - according to A. I. Dzhenkoul' and A. I. Doonov), according to investigation by the expedition (1958).

See page 153 for transliteration of place names.

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Figure 14. Map of distribution of young forest in the region of the fall of the Tungus meteorite. 1 - forest 40 years of age and younger, except young stands of birch; 2 - forest more than 40 years of age with admixture of 40-year old forest; 3 - forest more than 40 years of age; 4 - new slash fires; 5 - stands of birch.

Legend to Figure 13.

1. Kimchu
2. Dzhenkoul'
3. Lake Cheko
4. Forest Map
5. Kulik's Base
6. Ukagit
7. Neutral Zone
8. Pristan'
9. Khushma
10. 1958 Expedition
11. Florenskiy
12. 1958 Expedition
13. Shakhorma
14. Doonov
15. Forest Map
16. Makikta
17. Chamba
18. Krinov

Legend to Figure 14.

1. Kimchu
2. Lake Cheko
3. Kimchu
4. Cheko
5. Kulik's Base
6. Mt. Farrington
7. South Bog
8. Ukagit
9. Pristan'
10. Khushma
11. Ukagitkon
12. Lower Dulyusha
13. Upper Dulyusha
14. Chavidokon
15. Mt. Shakhorma
16. Mammoniya
17. Chamba
18. Khovorkikta
19. Lower Lakura
20. Upper Lakura
21. Chamba
22. Vanavara
23. Podkamennaya Tunguska
24. Chamba
25. Vanavara

Transliteration of numbered Russian place names.
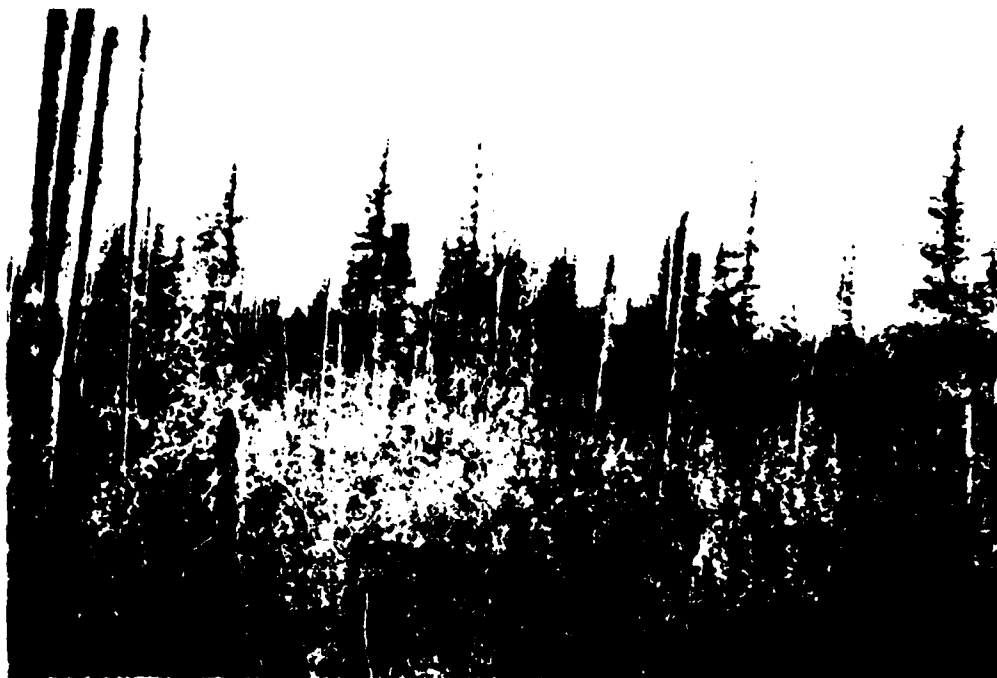
Figure 15. Locality several kilometers west of South
Bog which is characteristic of the "neutral zone".

by fires.[1] As early as 1953, K. P. Florenskiy (Ref. 10) noted that he
could not establish signs which would point out such a picture of the
event.

Our observations can be formulated in the following manner.

1. Close to the center of destruction many old breaks in

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[1] Our observations of old burned over areas do not confirm the speci-
ficity of these signs.

branches do show traces of burns; that is, in general they confirm the old rule: "There are no breaks without burns" (Ref. 14). This clearly defines the sequence of events in which burns occurred after the action of the shock wave.

2. Traces of burns on the bark remaining on the bare trees without tops (pillars) do not have any definite orientation toward the central part of the felled forest. They are of a ring-like nature here and there; at times their orientation is indefinite; in a considerable part of the region burns are predominant on the east side of the pillars, indicating the prevailing direction of the wind at the time of the fire.

3. Individual dry stumps or trees bear clear signs of prolonged burning, that is, there is no doubt at all that an instantaneous burn, if indeed there were such, is very thoroughly masked now by some forest fire.

The presence of two well-developed living twin larches within the bounds of the South Bog which was established by B. I. Vronskiy contradicts the version of instantaneous burns. After one of them was felled, it was found that it was 104 years old (Figure 16). These trees did not bear any traces of burns and were preserved because they lived in the midst of the bog, far from the shore where the fire which destroyed the living vegetation in this part of the region in 1908 could reach them.

4. It is probable that the fire was caused by the catastrophe. In addition to the above mentioned evidence, this is corroborated by the nature of the burns on standing trees which showed that trees which were still green but already broken were burned. This can be seen from the typical burning of holes into the trees around accumulations of tar (dried out trees were burned more evenly).

The lack of traces of burns on parts of trees covered at that time by new bark burned only on the surface (Figure 17).

5. Nevertheless, this fire differed from typical taiga forest fires in that it had the nature of a crown fire (the tops of the trees were burned), and a considerable area about the central part of the felled forest was included in a comparatively uniform manner. It can be considered that the forest fire and the felling of the forest were caused by the same complex phenomenon. (The general boundary of the fire approaches the boundary of mass felling of the forest. We explain this by the fact that it was the heaps of fallen trees which were burned. It was clearly seen in individual areas that further spread

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Figure 16. One of two twin larches discovered within
the bounds of the South Bog, 350 meters east of the
North Islands. The second larch, whose age was 104
years, was cut down.

of the fire was restricted by natural barriers - the river (Chavidokon)
or the bog (West Bog)).

Peculiarities of Development of the Trees. Statements are
encountered in the literature to the effect that vegetation in the
region of the fall of the meteorite is of a stunted nature, and it has
even been suggested that this could have been caused by saturation of
the soil with particles from the meteorite which were rich in nickel
(Ref. 2).

The over-all intensity of growth of trees is subject to sharp
fluctuations under the conditions which prevail in a mountainous and
swampy region with irregular development of permafrost; sections of
stunted forest are encountered with sections of full-sized forest and
it is not always easy to judge the actual age of trees from their out-
ward appearnce.

Thus, at first glance, many old trees are growing in the immediate vicinity of the central area of felling (pines and larches) whose diameter exceeded the diameter of dried out standing trunks having an age of 100 and even 300 years. However, a study made by Yu. M. Yemel'-yanov and others on Kobayev Island, on Stoykovich Mountain, and in other places showed that the number of annual rings in the majority of such trees did not exceed 35-40 with an average ring thickness of about 4 mm (Figure 18). At the same time, the thickness of individual rings reached 9 mm, which indicates very favorable conditions for growth. Prior to the fall of the Tungus meteorite, the annual growth of trees was 0.2-1.0 mm. Many old trees which were distinguished by accelerated growth after the fall of the Tungus meteorite were discovered in more distant areas--in the Khushma River valley, in the upper reaches of the Makikta River, and other places. In 1908, for example, the annual growth of trees was maintained on a level of 0.4 mm for pines and 0.16 mm for firs; after 1908 the annual growth of pines was about 1.6 mm and firs about 1.0 mm (Figure 19).

Figure 17.   ıed tree in the valley of Churgima Creek.
When a forest fire was caused by the fall of the meteorite, the wood did not burn where it was covered with green bark.

Figure 18. Cross-sections of trees from Mt. Stoykovich,
taken in 1958.   Above - living larch 40 years old; Below -
a larch which died in 1908 at an age of 300 years. Photo-
graphs on same scale.

One can draw the following conclusions from the field data.

Young trees grow well on the sites of forest fires; old trees which had been stunted prior to the fire but which remained undamaged when the forest was thinned out after 1908 enjoyed intensified growth (Figure 20); old trees which grew in unthinned stands do not show indications of a change in growth in 1908; old trees which had been growing under favorable conditions prior to 1908 showed a narrowing of their annual rings for several years after the fire, obviously a result of losses of branches and burning of their needles, subsequently followed by a restoration or even increases in their annual growth. It is obvious that there were trees with heavily damaged branches and needles which did not recover and died several years after the fire, but it is difficult to find them due to the impossibility of dating their death. Thus, there is no doubt as to the significance of biological indicators in revealing the peculiarities of 1908 and general changes in conditions caused by the fall of the meteorite.

More reliable conclusions on biologically active factors (more light due to thinning of the forest, the effect of ash fertilizers, changes in permafrost conditions, the possible effect of trace fertilizers, et cetera) based on detailed study of cross sections of trees and subsequent specialized observations in the area.
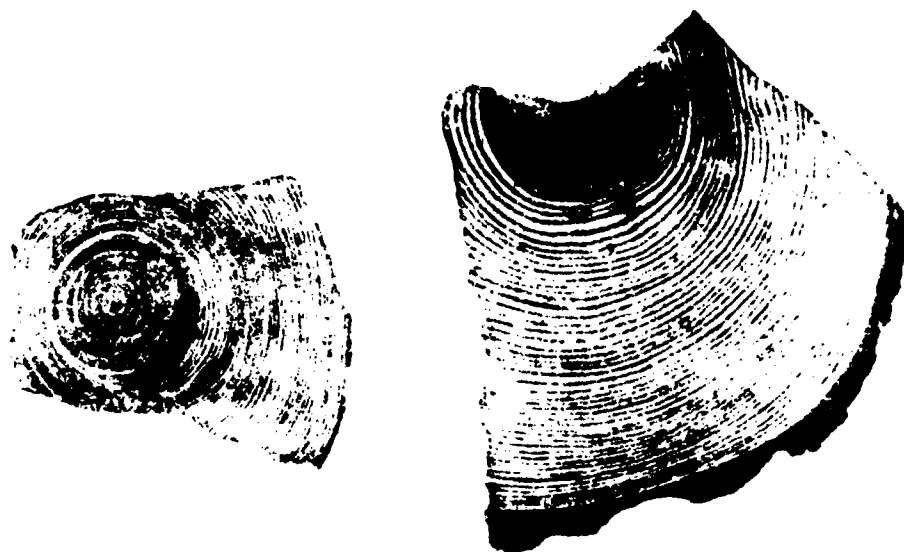
Figure 19. Cross-sections of trees more than 100 years old, taken in 1958. A difference in the rate of growth prior to and after 1908 is noticeable. Left - fir; Right - pine.

It seems that one can assume that the effect of the explosion of 1908 on the growth of trees was not of specific stunting (rather, it was quite the opposite).

Searches for Meteorite Craters and Destruction on the Ground. It should be noted that all our attempts to specify a "dry stream bed", "holes", and other direct traces of the meteorite were unsuccessful. Certain rumors which were current among the people in Vanavary turned out to be unfounded in all cases in which we were able to reach the primary source.

We were not able to discover any traces at all of a ground explosion which could correspond to energy of 10^{20} - 10^{23} ergs.

During a trip across the upper reaches of the Makikta River, along the watershed of the basin of the Khushma River and the Bol'shaya Lakura, then along the Chavidokon River and the left bank region of the Khushma River, we noted the foregoing features (K. P. Florenskiy, Yu. M. Yemel'yanov).

We discovered a lake formed from the felling of the forest in the upper reaches of the Makikta River. It has disappeared now, but it was noted on the map. Judging from the structure of the lake bed, it existed for several decades. The lake was about 100 meters long and 40-50 meters wide. In spite of all this, no particular destruction was noted in this area; and the lake was formed by a group of trees which had been felled across the river in 1908, was covered with a deposit of earth and rubbish, and thus accidentally formed a strong dam. Perhaps the same is true of dammed parts of the "river of fire" of which L. A. Kulik heard (Ref. 1, page 13), if we consider that the "collapse of cliffs along the river bank" was the imagination of the story teller or the interpreter.

The "large holes" on the left bank of the Chavidokon River (4 kilometers from the mouth), which had already been seen by K. P. Florenskiy (Ref. 10) (the river is called the Chavida on his map), were inspected. A repeated inspection confirmed their karst origin. Some of these holes were large (about 50 meters in diameter and 7 meters deep) funnel-shaped holes with white and rose-colored gypsum outcrops on their bottoms.

A large outcrop of gypsum up to 10 meters thick and up to 40-50 meters wide was discovered on the left bank of the Khushma river between the mouth of the Chavidokon River and Pristan'. Individual blocks of rose-colored gypsum are unusual in this region. Perhaps this is what I. V. Yelkin meant when he told L. A. Kulik of a strange rock "like a deer, and like a Dutch oven" on the bank of the Khushma (Ref. 1, page 146).

The ruins of a grain storehouse (Figure 21) were discovered in

the vicinity of a bend in the Khushma River, a little above the mouth of
the Chavidokon River. The ruins, which were on a small dry, grassy
ridge in an unforested area, were quite well preserved. It was clear
that the destruction of the storehouse (which stood on pillars) was con-
nected with the general felling of the forest in this region. No traces
were noted of burns on the ruins of the storehouse and no remainders of
utensils were found (except birch bark boxes). According to the stories,
the storehouse had belonged to Vasilii Il'ich Onkoul' (Dzhenkoul'),
known as V. I. Il'yushonok, the uncle of Andrey Ivanovich Dzhenkoul',
our guide.
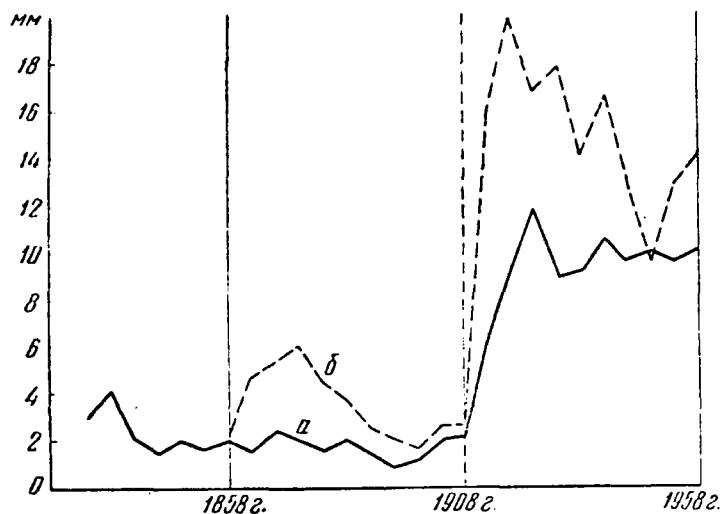
Figure 20. Five year growth in the diameter of trees
which survived 1908. Measurements were made along one
radius. The diameter was taken to be the doubled value
of the radii.   a - fir; b - pine.

The forest suffered little, in general, in this region and the
Evenki visited this place. A. I. Doonov states that he had found the
bones of deer which had died in 1908 in the 1920's, when he was a boy.

Another group of depressions which was inspected by K. P. Flor-
enskiy and I. T. Zotkin on advice of A. I. Doonov was found at a dis-
tance of 4-5 kilometers from the mouth of the Momonnaya River, a left-
bank tributary of the Chamba River. Several small (diameter of 15-20
meters) round, but irregular holes filled with water were found in the
swampy river valley, on its left bank. Their peat edges showed traces
of heaving and were covered with an old forest. Their origin could not
be established reliably, but they appeared to be of a thermokarst nature.
Judging by the fact that dried out trees were found in the holes and an
old forest grew around them, their origin does not seem to be of catas-
trophic nature.
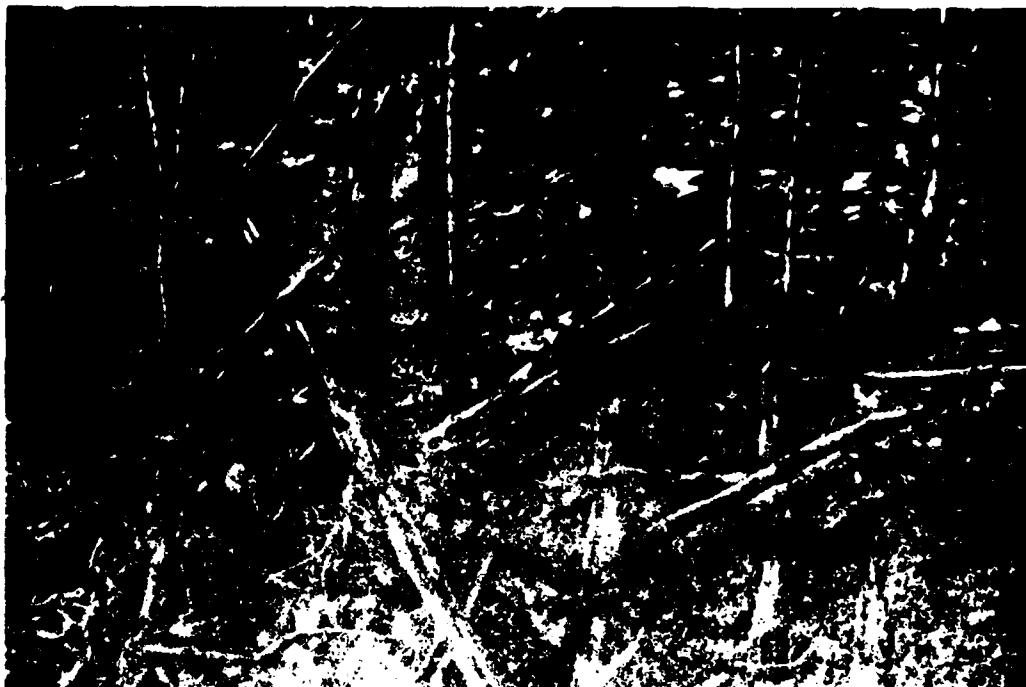
Figure 21. Remains of ruined storehouse near a bend in the Khushma River.

Figure 22. The South Bog. Peat ridges and individual trees are to be seen here. No trace of heavy destruction was observed here. The picture was taken from the North Islands located in the South Bog.

The South Bog (Fig. 22) was traversed four times (K. P. Floren-skiy, Yu. M. Yemel'yanov, and B. I. Vronskiy) as one of the suggested sites of the fall of the meteorite.

At present the South Bog can be crossed everywhere in the summer except for small individual areas in the vicinity of rifts. It is a typical swamp overgrown with moss crossed by irregular, denser ridges covered with stands of dwarf birch. We did not note any traces of destruction which could be connected with a mighty explosion within the bounds of the swamp. This is indicated by the remains of old dried out trees which were encountered in all the drier parts of the swamp and the two previously mentioned living larches with an age of more than 100 years. There are no traces of ejection of rock or peat on the banks of the swamp which one might expect from an explosion. There is no doubt in our minds that the possibility of the
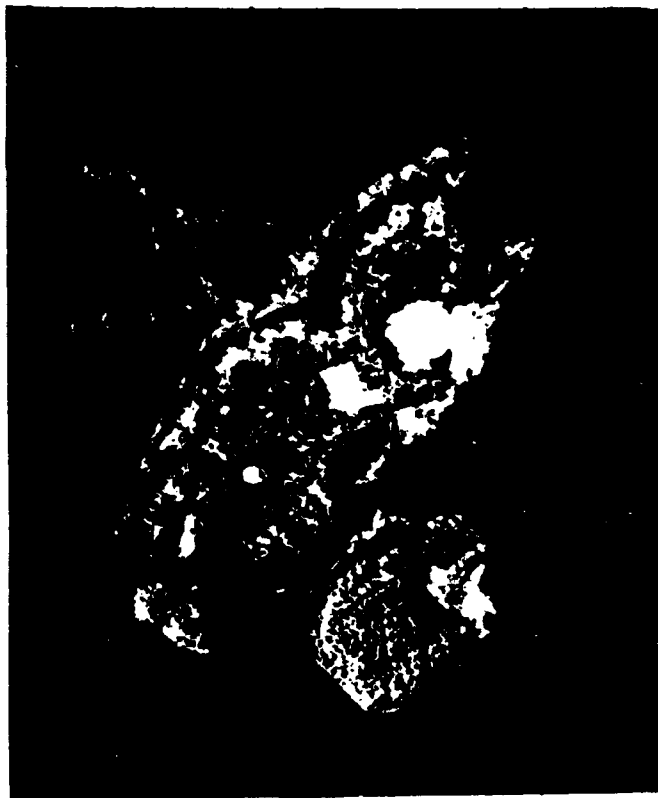
Figure 23. The North Islands. Aerial photograph on a scale of 1 : 5000 taken in 1938. The ridges in the bog, trees on the islands, and Klyukvennaya Crater can be seen.

existence of a crater hundreds of meters in diameter and lasting for
50 years should be ruled out. On comparing the aerial photographs of
1938 and 1949 it can be stated that the microrelief of the South Bog
is, in general, distinguished by its constancy. A swamp which has
been overgrown irregularly and forms a system of individual ridges
(called "valy" in the literature on the meteorite) is nothing unusual
and is characteristic of Siberia (Figure 23).

The islands scattered about the swamp are composed of peat and
have the character of peat hillocks. Some of them retained clear
traces of fire. Judging by the age of the lichens which had not yet
reached full development, one may consider that they correspond to the
fire of 1908.

Figure 24. A stump in the middle of Klyukvennaya Crater.

An inspection of the North Islands of the South Bog (Figure 23)
shows without doubt that the growth of the peat hillocks (and deepen-
ing of the craters) is continuing to the present time. This is clearly
evident on the southeastern edge of the Klyukvennaya Crater where
fresh outcrops of curved layers of peat which still preserve general
parallelness of the layers can be observed. The dried stump of a
broken tree remains in the center of the Klyukvennaya Crater (also in

the Suslov Crater), which indicates its thermokarst nature (Figure 24).

All the members of the expedition agreed that the South Bog could not be the ground center of the explosion which caused the general felling of the forest.

Of course, this statement is not connected in any way with the possibility of individual meteoritic masses falling into the South Bog which did not give rise to mighty explosion phenomena.

It is wholly probable that a general change in the heat regimen of the region connected with the fall of the meteorite in 1908 (a sharp decrease in forestation, a mighty forest fire with destruction of the moss cover, the destruction of the cover by uprooting of trees and, possibly, the fall of individual pieces of the meteorite) could have had a sharp effect on the permafrost conditions. Apparently it is with this factor that we must connect the general change in the condition of the swamp, which was pointed out by Lyuchetkan. We see corroboration of this in the works of L. V. Shumilova who established the existence of a change in peat-forming conditions since 1908. It is possible that an intensified formation of thermokarsts and growth of peat hillocks which so surprised L. A. Kulik began at just this time.

This problem should be studied with the aid of an experienced specialist in swamps who is familiar with regions of development of permafrost.

Thus, the 1958 expedition found no phenomena at all of ground traces of the collision with the meteorite. It is impossible to deny the existence of small craters not connected with the general destruction of the forest since such a detailed investigation of the entire area of the region was beyond the reach of our expedition.

Samples of the Soil and Their Study. As already pointed out, there are good grounds for assuming that the fall of the Tungus meteorite must have been accompanied by considerable scattering of its substance, no matter what the process of its destruction may have been. The probability of finding such finely dispersed particles is much greater than that of finding large pieces of the meteorite. If the meteorite consisted essentially of iron (Refs. 11, 12), such particles would be easily separated and their meteoritic origin could be established by their chemical composition. Finding iron particles in a sample taken in the Vanavary region in 1953 provided grounds for hoping that they would be preserved up to the present. About 80 samples of the soil were taken during traverses for this purpose.
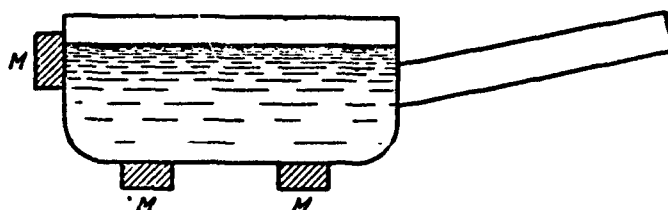
Figure 25. Diagram of washing trough; M-magnets.

Level areas in which one would scarcely expect to find con-
siderable changes in the thickness (washing in or out) of the soil
and in which there were no traces of destruction of the integrity of
the soil were selected for taking samples.

The grass or moss covering an area of about 5 square decimeters
was removed by hand from each site. A layer of the soil with turf,
with a thickness of about 5 cm, was cut with a spade down to the sub-
soil or down to the podzol A_2 horizon. Roots were separated from the

samples by washing them out in a magnetic washing trough or in a
portable magnetic washing drum and the soil itself was washed.

Numerous observations showed that the rate of growth of the
soil in these regions was considerable less than 5 cm in 50 years and,
consequently, the layer corresponding to 1908 would be included in the
samples.

The magnetic washing trough (Figure 25) was an aluminum trough
or a pan of sufficient size (diameter of about 30-35 cm) with three
multipolar Sochnev magnets fastened to the outside; two of them were
placed on the bottom of the trough and one was fastened to the side in
such a manner that the elutriated particles would pass through a mag-
netic field when the suspension was poured out.

The magnetic concentrates were washed carefully in the trough in
a manner like that used in studying heavy fractions of clay and sandy
soils (K. P. Florenskiy and B. I. Vronskiy).

The magnetic pan was also made of aluminum (Figure 26) and had
several sieves for facilitating washing. Sochnev magnets were

arranged in two successive series in the trough of the pan in a special pocket in such a manner that the size of the slit through which the suspension was poured off would not exceed 3-5 mm. The suspension was collected in a pail and passed through the trough several times in order to obtain complete recovery of the magnetic fraction.

Such washing ensured a sufficiently complete recovery of the magnetic sandy fraction with a grain size above 0.1 mm and, in particular, yielded magnetic grains of several hundredths of a millimeter. Smaller particles could be lost completely. Washing was carried out to the so-called gray concentrate, which still contained a considerable amount of nonferrous minerals. Pebbles which were contained in samples were removed by hand by straining the suspension through the fingers and were carefully examined.
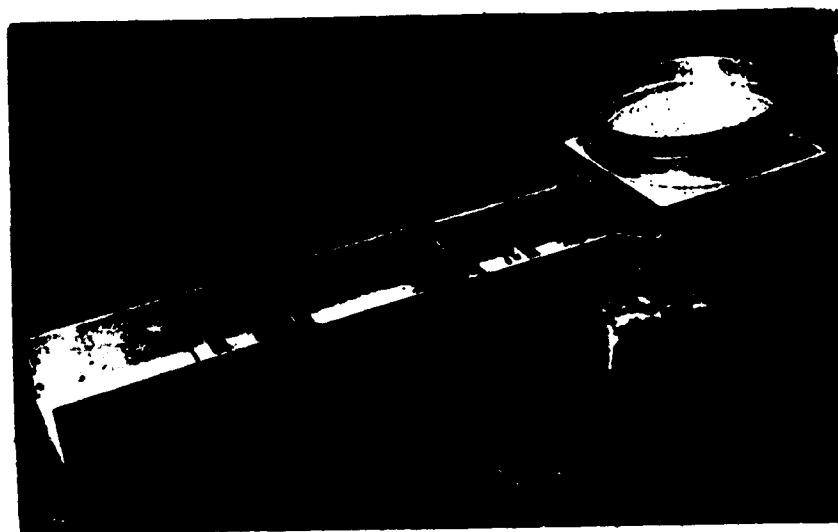
Figure 26. Pan equipped with two magnetic traps.

Dried concentrates were beneficiated once again by a magnet and were subjected to chemical analysis (P. N. Paley, Yu. M. Yemel'yanov).

A hydrochloric extract of the concentrates (sample of concentrates of 0.1—1.0 grams), obtained by boiling, was subjected to visual colorimetry with ammonium thiocyanate and dimenthyl glyoxime. In this way the analyst achieved equality of color with standard Ni" and Fe"' solutions. The sensitivity of the reaction corresponded to about 0.5 mg of Ni or Fe in the entire sample of concentrates. After obtaining a number of negative results for Ni content, another method was

applied: the most magnetic fraction was separated out of the concentrates and examined under a binocular glass (O. A. Kirova). Individual iron particles separated out under the glass were subjected to chemical analysis. Weighing was replaced by chemical determination of the absolute Fe content in the particles and the determination itself proceeded by a like method; in this case the determined minimum of Ni amounted to several tenths of gammas.

Soil samples were duplicated and sent to Moscow in untouched form for more careful and comprehensive study (particularly the silicate part). In addition to such typical samples, we separated the magnetic residues from a number of samples from Kulik's collectionswhich had been left on the wharf, and soil samples were taken from large areas (about 6 square meters) on the North Bog and in the vicinity of Pristan' on the Khushma River.

We had to give up the original plan for taking samples in accordance with a uniform grid and made it more dense toward the center (refer to Figure 2) since our samples persistently showed lack of iron meteorite particles while the available data (Refs. 11, 12) connected them with the central part of the region adjoining the South Bog.

Individual scales and bits of iron were noted and separated repeatedly in the collected samples during mineralogical study. No patterns at all were discovered in their territorial distribution. When chemically analyzed it always turned out that they either showed no reaction at all to nickel or that they contained only traces of nickel. This composition forced us to deny their meteoritic origin and to recognize them as particles from the iron tools with which the soil samples were taken.

Very small, probably magnetite and silicate spherules, one to four per sample, were discovered in a number of samples, without any definite territorial patterns. Only one sample, taken at the mouth of the Ukagitkon River, a left tributary of the Khushma River, by O. A. Kirova, contained a large quantity (212) such spherules (Figure 27), whose chemical composition has not yet been investigated. The sample was taken in the floodplain of the river, and secondary concentration of the spherules from washing of the soil is most likely.

These spherules are of a simple structure and at times are hollow; in external appearance they are indistinguishable from the spherules of obvious meteoritic origin described, for example, by Ye. L. Krinov (Ref. 13). We are inclined to acknowledge their cosmic origin, but do not see any basis for stating that they are necessarily connected with the Tungus meteorite. It is possible that they are traces of meteoritic dust which is distributed everywhere.

It should be added here that the method of studying the samples did not ensure complete separation of the smallest hollow spherules, and this question can be reexamined after studying the duplicates of soil samples under laboratory conditions.
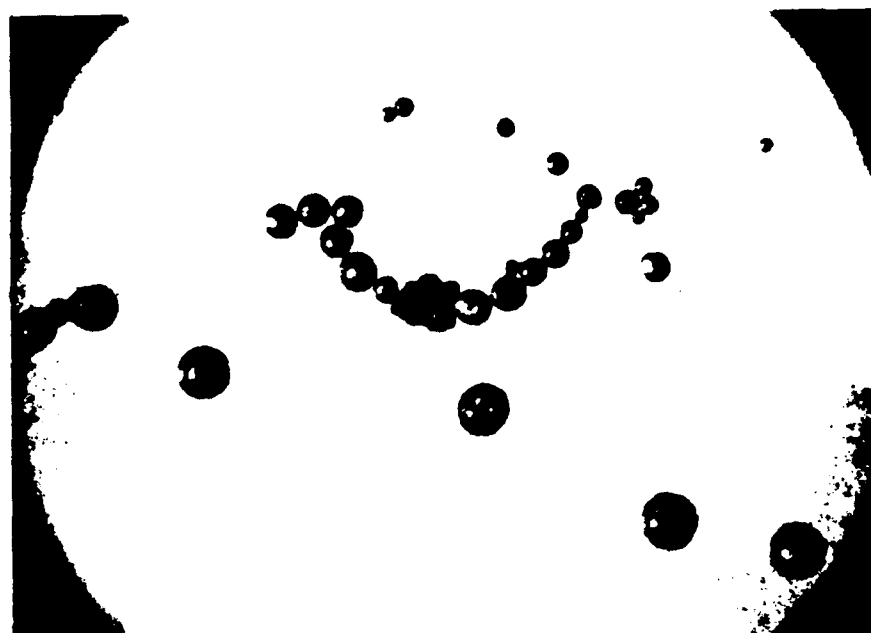
Figure 27.   Spherules from sample taken at the mouth of Ukagitkon Creek.

Thus, one can draw the following conclusions from field study of the iron particles:

1.   The procedure for taking and concentrating soil samples was carried out properly since small particles of iron and even the finest magnetite spherules were preserved in the samples.

2.   No patterns were discovered in the distribution of these iron particles.

3.   All the iron particles which were investigated were associated with iron of terrestrial origin and not a single large (more than 0.1 mm) obviously meteoritic particl   was discovered.   (Meteoritic particles were discovered by A. A. Yavne˘   in samples which were stored and processed on the premises of the KMET (Committee on Meteorites).   Their absence in the samples taken by Kulik, which had been stored at Pristan' on the Khushma River, compels us to assume the possibility of contamination of the Moscow samples with iron dust from sawing other meteorites).

4.   The fine magnetite spherules which were found are probably of

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cosmic origin, but there are no grounds as yet for identifying them with residues of the Tungus meteorite.

In addition to the concentration method for searching for iron particles, we made use of a method for searching for "random" particles which was based on the use of a staff with a magnetized end during trips. The material which adhered to the magnetic tip was cleaned off from time to time, examined under a binocular glass and, if necessary, subjected to chemical investigation. No iron meteorite particles were found by this method either.

On arrival at Moscow, several samples of soil and peat from the vicinity of the South Bog were transferred to the Institute of Geochemistry and Analytical Chemistry of the USSR Academy of Sciences to determine their radioactivity. Measurements made there under the guidance of Professor V. I. Baranov did not show any increase over the normal radioactivity of similar soils from other regions.

Other Samples. In addition to soil samples and cross-sections from trees, samples of bark were taken from broken and burned trees, old branches with traces of burns, parts of the ruined storehouse, etc. An attempt was made to take samples of mud from the bottom deposits of the small lake in the vicinity of Pristan'. These samples were to be subjected to comprehensive study in Moscow.

General Conclusions

1. The absence of large destruction in the central part of the felled forest--the South Bog--the absence of visible craters from the explosion of the meteorite, the presence of a "neutral zone"--a standing forest in the center of the catastrophe--the weak sheltering of trees from the action of the shock wave along the Churgima Creek--all this permits us to assume the basic direction of movement of the wave in this region was downward--that is, a high position for the center of the wave. (The first investigator of the fall of the meteorite, L. A. Kulik, also considered that the action of the shock wave was directed from above: "The meteorite struck the basin with its hills, the tundra, and bog with a fiery stream from its incandescent gages and cold bodies and, like a stream of water striking a flat surface, sprayed out in all directions just as the stream of incandescent gages with a swarm of bodies smashed into the earth and brought about this mighty picture of destruction by its direct action and also by its explosive transmission of energy." L. A. Kulik. Za Tungusskim divom. (On the Tungus Marvel), Krasnoyarsk, 1927.)

2. The amount of traveling involved in the work did not permit any conclusions as to the absence of the fall of even large pieces of the

meteorite without extensive crater formation (of the type seen in the fall of the Sikhote-Alin' meteorite, for example) in any part of the region investigated.

3. We did not establish the specific nature of burns on trees which had been observed by L. A. Kulik and Ye. L. Krinov. Judging by the fire which had occurred, however, one can speak of numerous centers of damage whose occurrence is also most likely in the case of action from above. The general boundary of the fire coincides closely with the boundary of total felling of the forest. An accurate determination of the boundaries of the forest fire could scarcely be of serious interest since further spread of the fire occurred through the usual means, which dims the picture of the original conflagration.

4. The shape of the zone of mass felling of the forest and the eccentric position of the neutral zone in it indicate the direction of action of the shock wave which was not regularly spherical and lacked central symmetry. It would seem that this is contradicted by the fact that the direction of the fallen trees is of a radial nature and axial symmetry was not noted in their orientation; the latter can be explained also by incompleteness of measurements.

5. At the time the field work was done we did not succeed in finding known material remains of an iron meteorite in the form of particles larger than 0.1 mm.

Taking into consideration that this was essentially the first attempt at systematic search for the material in the meteorite, such results can be explained by a whole series of causes: the dispersion of the material which was not picked up by the methods that were applied, complete oxidation of the iron particles in the 50 years, a considerable deviation of the ellipse of scattering from the center of felling of the forest. It is necessary to emphasize that the very assumption of the meteorite being an iron meteorite lacks adequate factual grounds. Pulverized particles of different composition (for example, stone) would be very difficult to find in the soil; no attempts at all have been made for such separation. It is premature to speak of the meteorite belonging to more rare types (carbonaceous, ice, etc.); further study of the collected material is essential.

6. A certain contradiction between the general atmospheric turbidity in the summer of 1908 and the indefiniteness of statements by witnesses concerning the smoke trail of the meteorite is noteworthy--nobody emphasized its size. This phenomenon compels one to assume the probability that the mighty dust tail of the meteorite had already broken off in the uppermost layers of the atmosphere, that is, the meteorite resembled a small bare comet (Astapovich, Whipple), the structure and composition

of which are still insufficiently studied.

7. The statements made by witnesses, which are stored by the Committee on Meteorites and which were examined anew by us, do not permit one to assert that there necessarily had to be a mighty explosion at the instant the meteorite fell, much less to speak of its terrestrial source. The statements invariably speak of the flight of a mighty bolide, but are of a quite general and indefinite nature in describing the details of the fall. This has permitted varying representations of the nature of the phenomena which accompanied the fall and different interpretations of the descriptions: "a pillar of fire" as the pillar from an explosion (Astapovich) and the track of the bolide in the plane of its trajectory (Krinov); "a cloud of smoke" as discharged products of an explosion (Astapovich), and smoke from a forest fire (Kulik), etc.

A general comparison of all the results which have been obtained permits one to conclude that classing the Tungus meteorite with the group of typical crater-forming meteorites is premature. The very theory of destructive meteorites should be supplemented by the case in which large destruction on the ground can take place without crater formation. It can be assumed that such cases are not exceedingly rare since all traces of the fall of actual crater-forming meteorites are of a prehistoric nature and can be preserved for tens of thousands of years.

On the other hand, destruction on the surface (for example, felling of a forest) is completely eradicated in a relatively short time (within several hundred years) and traces of them remain only in legends which enter the sphere of scientific study only by chance.

An examination of a generally similar case in which the destruction was caused by the action of a ballistic wave was made by K. P. Stanyukovich. At the request of Academician A. P. Vinogradov, M. A. Tsikulin and V. N. Rodionov completed a preliminary examination of the materials obtained by the 1958 expedition (Ref. 15). It showed that the observed destruction is most readily explained by the action of a ballistic wave from a meteorite which had undergone sharp deceleration.

Such deceleration inevitably takes place when a meteorite suddenly breaks into pieces. Such breaking into fragments can be of an explosive nature but the power of such an "explosion" can be not too great if it has converted a comparatively monolithic mass into a sufficiently dispersed state. Such "explosions" have been noted repeatedly in photographic traces of meteors in the upper layers of the atmosphere. Breaking up of meteorites is a most typical phenomenon. The relative force of breaking up can be increased readily by a whole series of complicating circumstances (elastic forces, sharp oxidation of the pulverized

products, and many others) and is not anything exceptional.

The relationship of the force of the action of a ballistic wave and a point explosion and the discovery of a number of parameters of a flying body is subject, on the present level of knowledge, to definite calculation if there is a sufficiently reliable and detailed map of destruction on the ground.

This explanation of the phenomenon gives rise to a large probability that the ellipse of scattering of the meteorite will not coincide with the epicenter of the action of the shock wave, which may also be taken into account in later work.

We have deliberately almost omitted explanations of the phenomenon since we are convinced of the total lack of value in any assumptions which are not supported by a sufficient number of reliable facts.

Prospects for Further Work

1. The factual base needed for quantitative calculation of the destructive wave and determination of the causes and conditions of its occurrence (the size and velocity of flight of a meteorite, the altitude and relative power of its explosion, etc.) should be a detailed map which should show all aspects of damage to the forest. The following data are of interest:
    a) the boundaries of zones of destruction of the forest with an indication of the percentage of damaged trees;
    b) numerical data reflecting the dependence of the felling of the forest on the relief at different distances from the center of the wave (shielding, lines of flow, etc.);
    c) sections with undamaged old forest;
    d) the orientation of fallen trees over a large area, clear up to the boundaries of partial felling;
    e) descriptions which cover the biological peculiarities of the forest (moisture, nature of the soil, the development of the root systems of the trees, etc.) in order to pin-point the peculiarities of the action of the shock wave.

The basic part of such a map can be compiled from the aerial map of 1939 on a scale of 1 : 5,000 for the central part of the region and the aerial map of 1949 on a scale of 1 : 50,000 for its peripheral parts. These maps should be subjected to special photogrammetrical processing which would permit conclusions on at least six radial strips from a common center.

Individual regions where it is not possible to determine the direction of fallen trees should be studied on the ground or studied

carefully from helicopters.

Such areas are, for example, the area between the Khushma and Elyuma Rivers, sections north of Lake Cheko, and others.

Work on counting the different types of damaged trees should be continued by investigations on the ground. It will probably be necessary to make several forest evaluation profiles about 40 kilometers long through the entire region of felled forest.

A sufficiently accurate map compiled in this way should be subjected to theoretical study in order to obtain unique answers to the questions which have been posed and the discovery of the interrelationships of the power of the ballistic and central explosion waves.

2. Searches for material remains of the meteorite in order to reveal its composition should be continued. At the same time, the soil samples which were sent in for separation of finely dispersed iron and stone meteoritic material should be studied carefully on one hand, and additional investigation of the region of the fall should be carried out on the other hand. The following questions merit attention in field work:

a) a layer-by-layer study should be made of bottom mud deposits of lakes in order to clarify the peculiarities of sediment formation in 1908;

b) searches for the ellipse of scattering of the meteorite along a continuation of its path to be made further to the north and to the south, starting with the region of the felled forest to boundaries obtained from calculations based on the probable height of the explosion and the inclination of the trajectory of the meteorite.

3. The following divisions can be stipulated for further work:

a) aerial observation from a helicopter of the entire region for a general description of felling, the discovery of the most interesting sections for ground investigations, and searches for small craters;

b) work of a biological nature in order to pin-point the effect of the fall of the meteorite on the growth of plant communities (forest and swamp vegetation);

c) swamp study projects for final determination of the effect of the meteorite on deformation of peat and changes in conditions in the South Bog with consideration of possible changes in permafrost conditions. A detailed study of the nature of thermokarst formations, which are so widely developed in the region of the fall with the aim of establishing their connections with the fall of the meteorite;

d) experimental work designed to clarify the rate of oxidation of small iron meteoritic particles in the soil under conditions comparable with those of the regions of the fall of the Tungus (and

Sikhote-Alin') meteorites.

In order to carry out all this work it will be necessary to expand laboratory processing of all collected material and to organize a comprehensive expedition equipped with helicopters and including representatives of different specialties. The organization of such an expedition should not be postponed since the traces of the fall of the Tungus meteorite are disappearing gradually and can be destroyed by a chance forest fire.

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VIII. ON THE DISCOVERY OF THE SUSUMAN IRON METEORITE

by B. I. Vronskiy

Russian Text Pages 135-142.

(The collection of information, the investigation of the site of the fall, and clarification of the circumstances of the discovery of the meteorite were fulfilled by the author on instructions from the Committee on Meteorites, Academy of Sciences, USSR).

The Susuman meteorite was discovered in the beginning of November 1957 in Magadan Oblast', in the basin of the Berelekh River--a large left-bank tributary of the Kolyma in its upper reaches. The coordinates of the site of the find are $62°43'17''$ North latitude and $148°07'49''$ East longitude (Figure 1).

The meteorite was discovered on Zarya Creek by the worker Solukha while he was loading rock from a mine which had been obtained by blasting (permafrost is found everywhere in the northeastern part of the USSR which cements friable rock into a dense monolithic mass so that it is necessary to employ blasting when working placer mines).

While loading rock from the shaft of the mine after routine blasting, Solukha noticed a large elongated stone which differed sharply from the surrounding shingle and pebbles in its color, size, and external appearance (Figure 2); he was astonished at its weight and decided that this was a large nugget of gold. However, several blows with a sledge hammer on the surface of the "nugget" showed this experienced worker that this was not gold, but a metal like iron, without knowing how it got into the placer mine at a depth of 32 meters from the surface of the ground.

Being a very inquisitive person, Solukha brought his find to the local geologist, P. N. Kamenetskaya and asked her to explain just what it was. Kamenetskaya could not give him a good answer. She took the stone, telling Solukha that she would try to study it more carefully during her leisure hours, then give her opinion. After two weeks Solukha recovered his find from her and turned it over to the chief mechanic of the mine, Reyngart, with a request that he should determine what the metal was.

Reyngart and other workers in the mechanical workshop became interested in the unique piece of metal. They decided to break it and find out what it contained on the inside. All the people in the
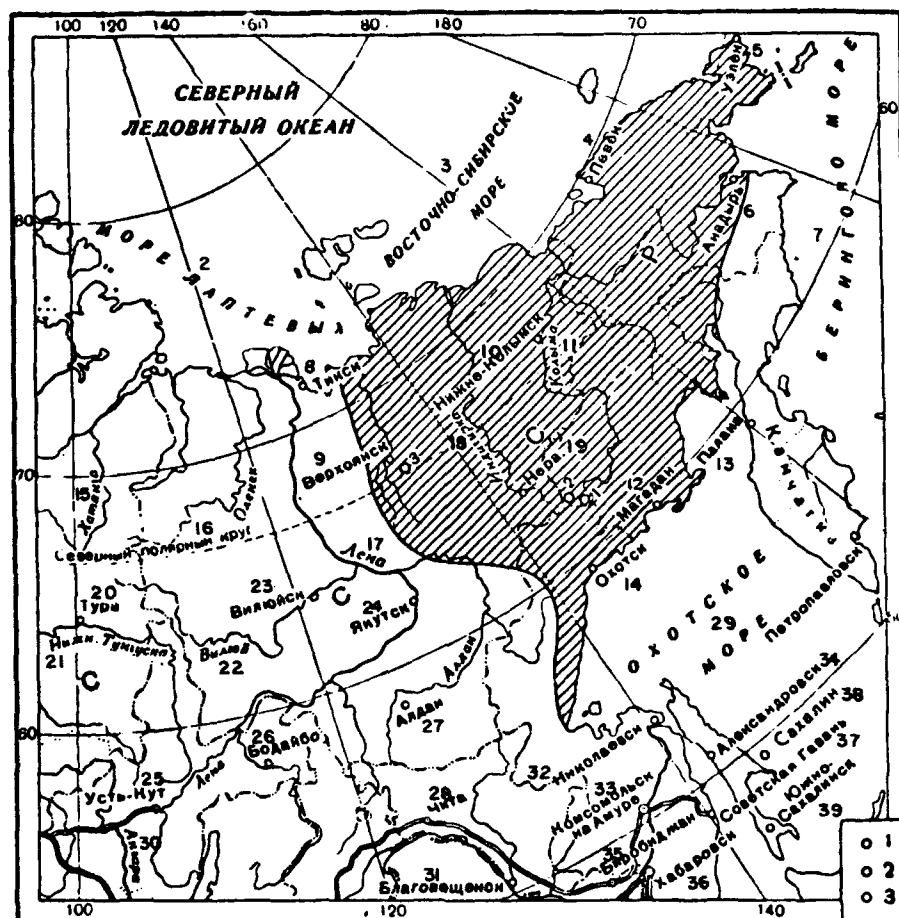
Figure 1. Map of discoveries of meteorites in Northeastern USSR (cross-hatched). 1 - Susuman; 2 - Mal'dyak; 3 - Burgavli

Figure 2. The Susuman meteorite.

Legend to Figure 1.

1. Arctic Ocean
2. Laptev Sea
3. East Siberian Sea
4. Pevek
5. Uellen
6. Anadyr'
7. Behring Sea
8. Tiksi
9. Verkhoyansk
10. Nizhne-Kolymsk
11. Kolyma
12. Magadan
13. Palana
14. Okhotsk
15. Khatanga
16. Arctic Circle
17. Lena
18. Indigirka
19. Nera
20. Tura
21. Lower Tunguska
22. Vilyuy
23. Vilyuysk
24. Yakutsk
25. Ust'-Kut
26. Bodaybo
27. Aldan
28. Chita
29. Sea of Okhotsk
30. Angara
31. Blagoveshchensk
32. Nikolayovsk
33. Komsomol'sk-na-Amure
34. Aleksandrovsk
35. Birobidzhan
36. Khabovovsk
37. Sovetskay Gavan'
38. Sakhalin
39. Yuzhno-Sakhalinsk

Transliteration of numbered Russian place names.

mechanical workshop spent a whole shift trying to cut the specimen with a sledge hammer and a cold chisel. By the end of the shift they succeeded in breaking the specimen into two unequal parts, chipping off a third small fragment weighing about 100 grams. The larger part turned out to have a weight of 12.1 kilograms, the smaller one 6.7 kilograms. The interior of the specimen did not turn out to be gold as they had hoped, but some gray metal resembling an alloy with coarse-grained macrocrystalline structure (Figure 3).

Reyngart, who was astonished by the unusual appearance of this metal, sent the small, chipped-off fragment to the chemical laboratory of the central mechanical repair workshops of Susuman Settlement for study. The specimen sent to the laboratory was studied by the head of the chemical laboratory, I. S. Kostyuk, who noted in his records that on 23 November 1957 the mechanic Pastokhov had obtained a flat metallic fragment for the chief mechanic of the Placer Mine imeni Frunze in order to determine its composition. The weight of the fragment was 101.72 grams. The specific gravity of the specimen turned out to be 7.8.

Figure 3. Surface of fracture, Susuman meteorite.

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Kostyuk noted the presence of a macrocrystalline structure in the specimen, also the presence of brownish-gray shiny inclusions between the crystals. A fracture of large crystals was fine-grained. A spark test showed that the carbon content was 0.1 percent. A non-metallic deposit could be seen clearly with a binocular microscope. The material could be drilled readily. Chips could be taken readily from the specimen and could be forged easily when cold. It was completely dissolved in hot hydrochloric acid. Dissolving first proceeded at a slow rate as if some sort of film were being destroyed, then became vigorous. Investigation with a steeloscope (British trade name) yielded a typical iron spectrum with a nickel content of 5-7 percent.

On the basis of the investigations which had been made, Kostyuk concluded that the specimen which had been brought in was part of an iron meteorite. He reported this information to Reyngart. The latter informed Solukha of this and transferred the two halves of the meteorite which were in his custody to the senior geologist of the geological prospecting office of the placer mine, Korobov.

The meteorite remained in the geological prospecting office until the autumn of 1958. Ye. D. Gudin, who replaced Korobov as senior geologist at the placer mine, sent both halves of the meteorite to the Committee on Meteorites of the USSR Academy of Sciences where it is being studied at present.

In March 1959 the author of this article succeeded in visiting the place where the meteorite was found. Accompanied by the senior geologist of the Frunze placer mine, Gudin, and the section chief, Rozhanov, we made our way up Zarya Creek through deep snow. The mine field had been worked out long ago, the mine had fallen in and it was utterly impossible to go into it. Only lonely protruding pillars and a snow covered depression marked the place where the meteorite which had been buried at a depth of 32 meters was taken from the ground.

We shall give a more detailed description of the surroundings in which the meteorite was found. The mine was located in the valley of Zarya Creek at a distance of 2.3 kilometers from its mouth. The meteorite was found close to a prospecting pit, at a depth of 32 meters from

the surface of the ground near the placer bed itself[1], in the midst of frozen river deposits of gravel and pebbles cemented by sand and a clayey material (Figure 4).

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[1] Bed is the term applied to original rock underlying loose river deposits.
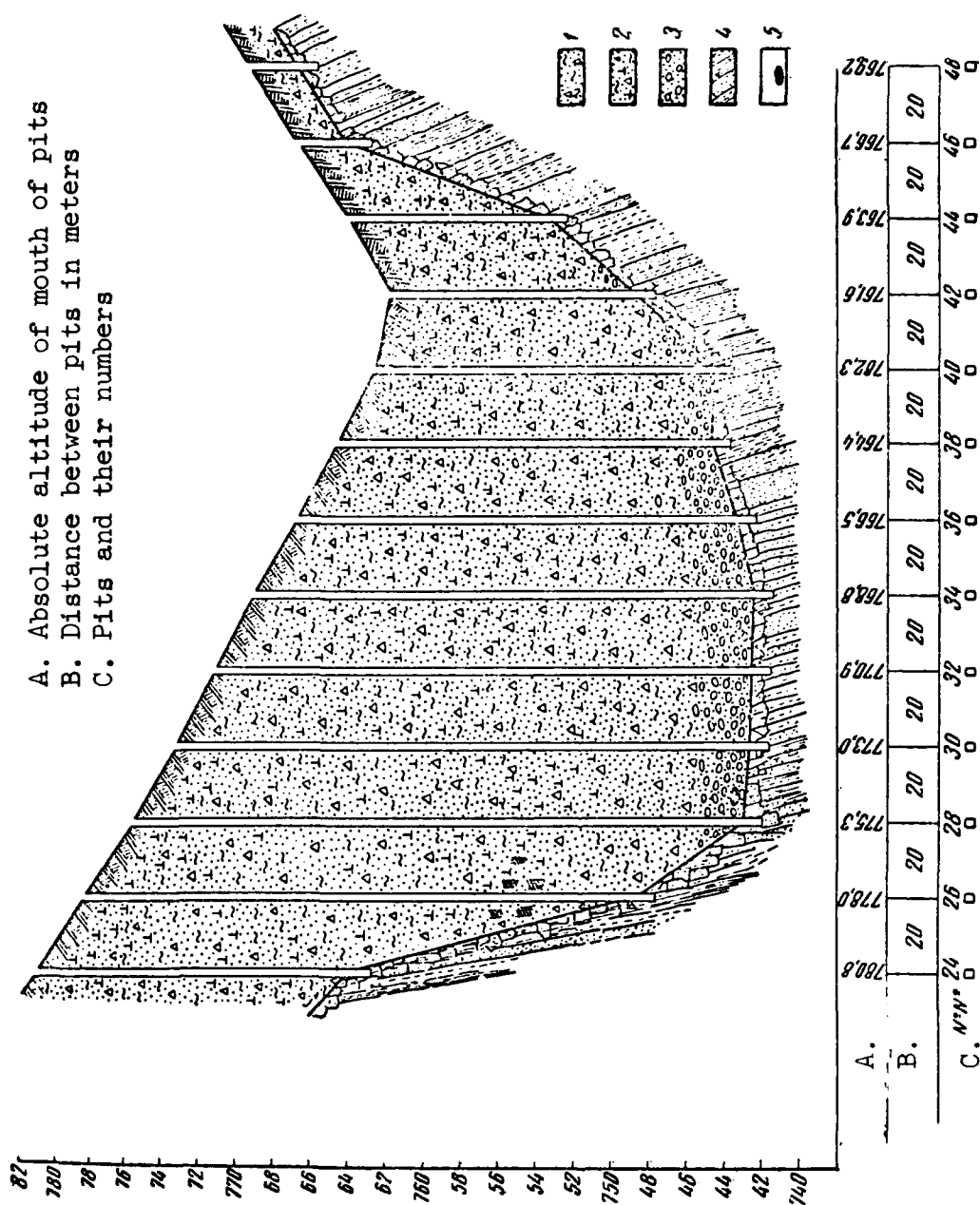
Figure 4. Transverse profile of valley of Zarya Creek with an indication of the site of the Susuman meteorite.

1 - sandy-silt deposits with shingle (colluvial); 2 - the same, with lenses of ice;
3 - pebbles with sand and clay (alluvial); 4 - bedrock; 5 - Susuman meteorite.

A profile of these friable deposits as determined by the pro-
specting pit is given below:

0.0 - 0.2 meters - vegetation layer;

0.2 - 0.6 meters - dense gray clay with a fine shingle of clay
and sandy clay shale;

0.6 - 2.2 meters - gray silt with shingle of clay and sandy clay
shale; individual ice layers;

2.2 - 4.2 meters - dirty ice (about 80 percent) with fine grained
gray sand;

4.2 - 8.6 meters - fine grained gray sand and silt with shingle
of clay and sandy clay shale of various sizes;

8.6 - 17.0 meters - sand, clay, and silt with shingle of clay and
sandy clay shale, primarily of medium size; frequent layers and lenses
of ice;

17.0 - 19.6 meters - shingle of medium and large sizes with sand
and clay; rare layers of ice;

19.6 - 23.2 meters - dirty ice with admixtures of fine grained
gray sand;

23.2 - 26.2 meters - shingle of clay and sand clay shale of var-
ious sizes with fine grained gray sand, clay and silt; frequent layers
of ice;

26.2 - 28.6 meters - coarse shingle and sandy clay shale with
sand, silt, and clay; rare, poorly rounded pebbles of sandstone and dike
rocks are encountered;

28.6 - 31.0 meters - silt with shingle of different sizes; insig-
nificant layers of ice;

31.0 - 32.4 meters - a mixture of shingle of different sizes re-
presented by sandy clay shales and sandstones, with poorly and well-
rounded pebbles, sand, and clay; well-rounded pebbles are rarely encoun-
tered (the amount increases in the lower horizons); the composition of
the shingle is sandy clay shales, sandstone and dike rocks; the meteor-
ite was found in the midst of this material at a depth of 32.2 meters;

32.4 - 33.4 meters - the bedrock, a gray coarse grained sandstone
heavily cracked on its upper portion and more dense with depth.

Zarya Creek flows into the Sylgybastakh River, a left tributary
of the Susuman River, near its mouth. The Susuman, in turn, is a left
tributary of the Berelekh River. The creek is about 3 kilometers long,
the width of its valley does not exceed 200 meters in its middle and
upper reaches, and reaches 300 meters in its lower reaches. The present
creek bed is poorly defined, there is almost no water in the creek. The
creek bed is somewhat closer to the left slopes of the valley.

Cross-sections along prospecting lines show that the underground
profile of the valley is trough-shaped with a wide thalweg and steep
sides. The valley is filled with friable deposits represented by collu-
vial, deluvial, and, to an insignificant extent, alluvial material. Col-
luvial deposits represented by silt, sand, and clay with an admixture of

shingle show the highest development. A large amount of layers and lenses of dirty ice, which reaches 50 percent of the total mass of the deposits, is observed among the colluvial deposits.

The attached profile along Line No. 23, near which the meteorite was found, gives a clear picture of the nature of the underground profile of the valley of Zarya Creek (refer to Figure 4). Alluvial deposits fill the bottom of the valley and lie directly on the bedrock. Their thickness does not exceed 1.5 - 3.0 meters. They are represented by well-rounded pebbles of different sizes, rounded boulders, and rare boulders among the sandy clay mass. The shingle is essentially sandy shale and sandstone. It is represented at times by dike rocks.

The territory in which the Susuman meteorite was found is located on the right bank of the Berelekh River and is associated with a region of development of small mountains with an absolute altitude of 800-900 meters which rise 200-300 meters above the level of the present valleys. The section is composed of sedimentary rocks represented by clay and sandy clay shales with seams of gray medium grained sandstones. The age of the sedimentary rocks is Upper Triassic. The sedimentary rocks have intrusions of dikes of igneous rocks represented by quartz porphyries and diorite porphyries.

The time of the fall of the meteorite can be determined only approximately. It is associated with the post-glacial period. This is indicated in particular by the presence of granite boulders in the deposits of one of the prospecting lines in Zarya Creek, probably due to the washing of glacial deposits which are no longer preserved in this area. The discovery of remains of the skeleton and hide of a musk ox in deluvial-colluvial deposits in the course of prospecting work close to Tangora Creek similar to the deposits developed in the valley of Zarya Creek corroborates this proposition.

The fall of the meteorite took place about 15-20 thousand years ago when the creek was flowing through a well-defined valley with thin alluvial deposits. A subsequent slow subsidence of the locality caused deluvial-colluvial masses to slip gradually from the slopes. When these masses filled the valley, they buried the meteorite at this great depth.

The permafrost which was developed in the area ensured its splendid preservation. The well-rounded appearance of the meteorite was apparently caused by two factors. On one hand it was affected to some extent by the atmosphere during its flight, on the other hand, it was subjected to the wearing and rounding action of the alluvial material in the stream after the meteorite had fallen to the earth's surface. The discovery of the Susuman meteorite reminds one of the Mal'dyak meteorite (Ref. 1) found in the summer of 1939 not far from the site of the discovery of the Susuman meteorite.

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Let us recall briefly the circumstances in which the Mal'dyak meteorite was found and give a short description of it.

The meteorite was discovered in the basin of the Berelekh River, in the upper reaches of Mal'dyak Creek, in an operating pit of a placer mine with the same name at a depth of 4.6 meters, in alluvial deposits. The latter was represented by shingle with an admixture of sand, gravel, and silty clay material (Figure 5). This was the first find of this sort over the vast territory of the northeastern part of the USSR which includes the basins of the Yana, Indigirka, and Kolyma Rivers and the adjoining regions of Chukotka, Kamchatka, and the coast of the Okhotsk Sea.
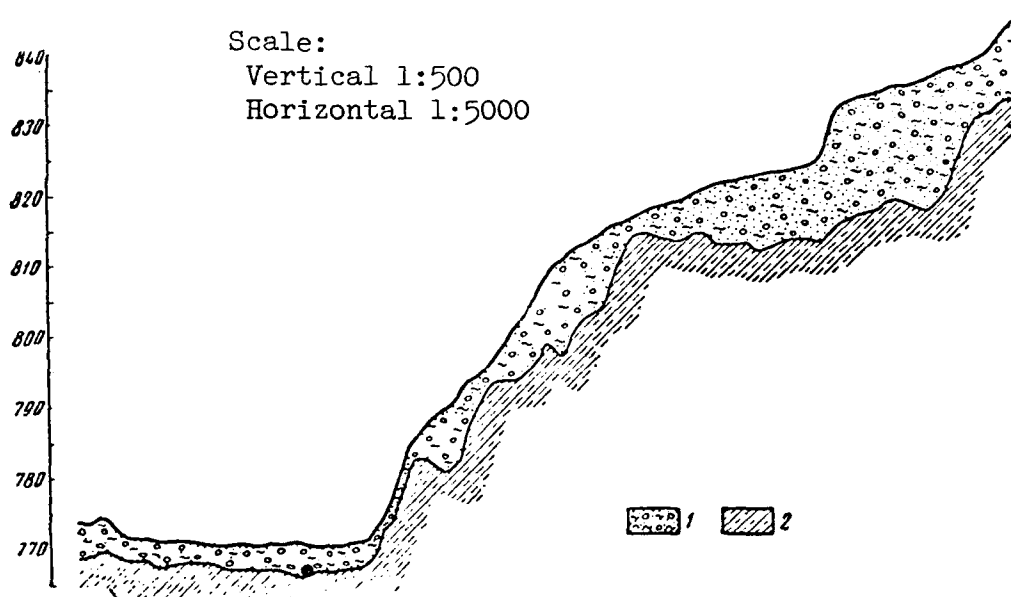
Figure 5. Lithological section of part of the valley of Mal'dyak Creek. The site of the Mal'dyak meteorite is shown by the circle.
1 - Alluvial deposits (pebbles with sandy clay material); 2 - bedrock (sandy clay shales).

The more accurate coordinates of the site of the discovery are

$62°9'$ North latitude and $148°10'$ East longitude.

The circumstances in which the Mal'dyak meteorite was found remind one in many ways of the history of the discovery of the Susuman meteorite. A worker of the placer mine who was taking samples in an operational pit in the vicintiy of prospecting line No. 8 noticed an unusual stone covered with a film of brown iron oxide. The large specific

gravity of the stone convinced the worker that he had found a nugget of gold. In order to verify this, the worker laid the stone on the ground and struck it sharply with his pick. Instead of the expected gold, a steel gray shining surface was displayed in the depression at the site of the blow, a sight which immediately refuted the gold theory. The disappointed worker was about to throw the stone on the tailings dump, but saw the mine geologist Borisov passing by and decided to show him the discovery and find out just what it was. Borisov concluded that this was a fragment from a prospecting drill which had been in the alluvial deposits for a considerable time. He took the stone with him and brought it to the prospectors' base as a humorous joke. The author of this article, who was the chief geologist of the mining administration at the time, inspected the strange rock when he visited the prospecting base at Mal'dyak and suspected that it was a meteorite. He took it with him and sent it to the mechanical workshop for sawing. The meteorite was sawed into two roughly equal parts. Each of the parts was polished on a grinder, then etched with dilute nitric acid. The clear-cut set of Widmanstaetten patterns which appeared completely established the cosmic origin of the discovery. The meteorite weighed 992.2 grams prior to sawing and its specific gravity was 6.8. The meteorite had an irregular, rounded pear shape. The comparatively low specific gravity is explained by the presence of a cavity with an exit to the exterior in the expanded part of the meteorite. The length of the cavity was about 3 cm and its width about 1.8 cm.

The cavity was filled with sand and gravel which had been pounded into the meteorite while it was in the river deposits and had been converted into a dense monolithic mass cemented by iron oxide. The latter bordered the interior surface of the cavity at a distance from one to four millimeters in irregular wavy concentric layers.

The cavity was apparently formed in the place of an unstable mineral inclusion which had been leached out, most probably troilite (Ref. 2). This circumstance and the considerable oxidation of the surface of the meteorite, together with the conversion of the friable material filling the cavity into a dense monolithic mass, indicate that it coincides with the time of the fall of the Susuman meteorite.

This assumption is based on the following data: in the first place, both meteorites fell a long time ago; in the second place, they were found at a comparatively small distance from each other. The site of the discovery of the Susuman meteorite is only 28 km south of the site of the discovery of the Mal'dyak meteorite, almost in a north-south line and displaced from this line by 4.5 km to the west. Moreover, both meteorites are iron meteorites.

The fact that the Susuman meteorite was found at a depth of 32 meters in alluvium buried under a thick cover of colluvial deposits while

the Mal'dyak meteorite was discovered in modern alluvium at a depth of 4.6 meters from the surface should not disturb us. The Mal'dyak meteorite could have been transported into modern alluvium from terrace deposits by washing. This phenomenon of washing and redeposition of terrace formations is widely developed in the middle reaches of the Mal'dyak.

It is difficult to imagine that there were two different falls of iron meteorites in the Berelekh Basin long ago which occurred within a short interval of time, judging by the age of the fall of each meteorite. The final answer to this question can be obtained after proper study of the Susuman meteorite and comparison of its chemical composition and structural peculiarities with like parameters of the Mal'dyak meteorite. In any event, the assumption that both these meteorites are parts of a single meteorite shower or group which fell in the basin of the Berelekh River 15 to 20 thousand years ago is not devoid of a solid foundation.

Unfortunately, requests for information have not produced any reports on the presence of other discoveries of meteorites in the basin of the Berelekh River in spite of the extensive development of prospecting and mining projects here in the placer mines of the ore deposits of the Berelekh River and its tributaries. The conditions of the discoveries of these two meteorites show how random finds of this sort are. It is possible that many similar finds have been lost due to the lack of information of the persons who found them, took them to be nuggets of gold, then after finding their mistake, threw them away.

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IX. THE LIFETIME OF COMETARY ICES IN THE FIELD OF PHOTON AND CORPUSCULAR RADIATION FROM THE SUN *

by V. I. Cherednichenko

Russian Text Pages 143-154.

(This paper was read before the expanded plenary meeting of the Committee on Meteorites of the Academy of Sciences, USSR, on 8 May 1959).

The question of the lifetime of cometary nuclei consisting of pure or impure H_2O, CH_4, NH_3, CO_2, C_2H_2, and C_2N_2 ices is of great importance in the problem of the origin of comets. The fact that NH, NH_2, CH, CH^+, N_2^+, CO^+, OH, C_3, OH^+, and CO_2^+ gases are observed in cometary spectra provides evidence of the presence of H_2O, CO_2, C_2N_2, NH_3, CH_4, and C_2H_2 ices in the nuclei of comets.

The majority of these chemical compounds are found on the planets and satellites of the solar system. The rapid age decrease in the brightness of short-period comets indicates the youthfulness of these comets and gives rise to a very probable hypothesis of a considerable content of ices in cometary nuclei. Such hypotheses were justified to a large extent in the work by Whipple (Ref. 1).

An attempt is made in this paper to calculate the lifetime of cometary nuclei consisting of pure ices and to compare the results obtained with the results obtained from cometary statistics (Ref. 2), also to discover the effectiveness of the process of assimilation of the decay products OH and H in the original parent H_2O molecules.

In calculating the lifetime of an ice cometary nucleus, we shall make a number of simplifying assumptions.

Let a spherical cometary nucleus of radius R_0 revolve about the Sun in a circular orbit of radius r, turning the same side to the Sun at all times. The circular cross section of the nucleus with an area πR_0^2 can be taken as the effective cross section of the nucleus for absorption

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*Commas in equations represent decimal points.

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of radiation from the Sun. If the albedo of cometary ice is A, the solar constant at distance of one astronomical unit from the Sun is E_O,

and the heat of evaporation of one molecule is L, then on the average

$dE = \dfrac{(1-A)E_O}{2r^2L}$ dt molecules will be evaporated from 1 cm^2 of the surface

of the cometary nucleus over the time dt and $N = 2\pi r^- \dfrac{(1-A)E_O}{2r^2L}$ dt mole-

cules from the entire hemisphere of the cometary nucleus. The decrease

in volume of the cometary nucleus due to evaporation will be $V = \dfrac{Nm}{\rho}$

where m is the mass of the evaporated molecule, ρ is the density of the cometary ice. The decrease in the radius of the cometary nucleus over the time dt is

$$-dR_{\infty} = \frac{V}{\pi R^2} dt$$

or

$$-dR_{\infty} = \frac{(1-A)E_0 m}{\rho L r^2} dt.$$

(1)

In case the comet is moving in an elliptical orbit

$$dt = \frac{P r^2}{2\pi a^2 \sqrt{1-e^2}} d\varphi,$$

(2)

where a and e are the semimajor axis and the eccentricity of the cometary orbit, P is the period of the comet, and φ is the true anomaly (Ref. 3).

Substituting the value (2) of dt into (1), we obtain

$$-dR_{\infty} = \frac{(1-A)E_0 m P}{2\pi a^2 L \sqrt{1-e^2}} d\varphi.$$

(3)

The lifetime of the cometary nucleus will then be found by integrating (3)

$$-\int_{R_{\infty}}^{0} dR_{\infty} = \int_{0}^{\frac{2\pi}{P}t} \frac{(1-A)E_0 m P}{2\pi a^2 L \sqrt{1-e^2}} d\varphi.$$

(4)

After integrating we shall have

$$t = \frac{\rho L D_{\infty} a^2 \sqrt{1-e^2}}{2(1-A) m E_0},$$

(5)

where D_{o-} is the diameter of the cometary nucleus.

In formula (5) we can assume without large error that the albedo of the CH_4, NH_3, CO_2, C_2N_2, and C_2H_2 ices will be close to the albedo of H_2O ice. The latter can be found from the Fresnel formula $A = \left(\frac{\sqrt{\epsilon}-1}{\sqrt{\epsilon}+1}\right)^2$.

For H_2O ice the dielectric permeability ϵ = 94 (Ref. 4). Then A_{H_2O} = 0.7. Setting A = 0.7 and L is 10^{-13} erg/molecule, expressing D_0 in kilometers, m in atomic weight units ($1.66 \cdot 10^{-24}$ grams), and substituting in the value of the solar constant E = $1.36 \cdot 10^6$ erg/cm^2-sec, we obtain

$$t = 2{,}34 \cdot 10^2 \frac{\rho L D_{o-} \, a^2 \sqrt{1-e^2}}{m} \; ; \tag{6}$$

where t is expressed in years.

The physical characteristics of cometary ices are given in the table.

Ice	g/cm^3	$L \cdot 10^{-13}$ erg/molecule	$m \cdot 1.66 \cdot 10^{-24}$ grams
H_2O	0.9	8.40	18
CH_4	0.52	2.08	16
NH_3	0.8	5.13	19
C_2N_2	1.45	3.72	52
CO_2	1.69	5.21	28
C_2H_2	0.57	4.16	26

The density ρ is calculated by the formula $\rho = \frac{nm}{a_1^3}$ where n is the number of molecules in a crystalline cell, m is the mass of the molecule, and a_1 is the crystalline lattice constant.

The values of n and a_1 were taken from (Ref. 4); L for H_2O, CH_4, NH_3, C_2N_2, and CO_2 ices from Whipple's work (Ref. 1); and for C_2H_2 ice from the work by Dobrovol'skiy (Ref. 5).

Using the transformed formula (6)

$$t = 2{,}34 \cdot 10^2 \frac{\rho L D_{o\leftarrow} \, a \, \sqrt{a^2 - (a-q)^2}}{m}, \qquad (7)$$

where a and q (the perihelion distance) are given in astronomical units and making use of the data in Table 1 and assuming that A = 0.7 for all ices, the author obtained the graphs shown in Figures 1 - 6 for values of the lifetimes of cometary nuclei consisting of CO_2, H_2O, NH_3, CH_4,

C_2N_2, and C_2H_2. The values $D_{o\leftarrow}$ = 0.25, 0.5, and 1 kilometer were taken for the diameter of the cometary nucleus. The values of the semimajor axes were in the interval $1.5 < a < 20$ (short-period comets); $0.5 < q < 4.0$, which corresponds to the change in the eccentricity $0.333 < e < 0.975$.

The scattering of solar radiation on the dense gas shell of the comet and the effect of the rotation of the cometary nucleus were not taken into consideration in calculating t. However, taking these quantities into consideration could not change the order of magnitude of t (Ref. 6). Observations indicate the great transparency of cometary atmospheres (Refs. 6, 7), consequently small attenuation of the intensity of solar radiation in passing through a cometary atmosphere. The absorption of solar radiation by the cometary nucleus is likewise little dependent on the rotation of the nucleus (Refs. 1, 5).

It can be seen from Figures 1 - 6 that the lifetime of cometary ices of spherical form with a diameter of $0.25 < D_{o\leftarrow} < 1$ kilometer lies within limits of $6.6 < t < 7 \cdot 10^4$ years. This result is in good agreement with S. K. Vsekhsvyatskiy's conclusion (Ref. 2) on the lifetime of short-period comets.

The results obtained are also valid in the case of cometary nuclei consisting of a mixture of easily melting (ices) and refractory (meteoric substances) components. As shown by Grushka (Ref. 8), the lifetime of ices in such cometary nuclei will be of the same order of magnitude as those given in Figures 1 - 6.

It is easy to show that photon radiation from the Sun plays the principal role in the evaporation of pure cometary ices.
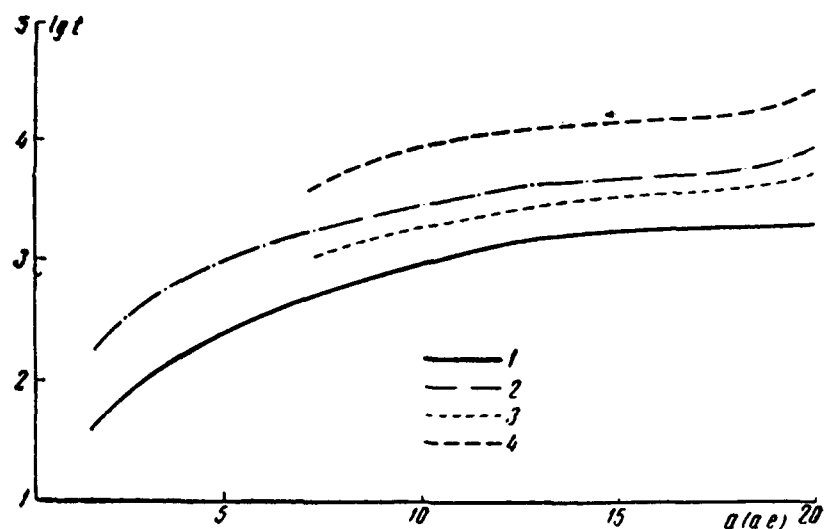
Figure 1.   Lifetime of cometary nucleus of H_2O ice (t in years).

1 - q = 0.5 astronomical units; D_{O-} = 0.25 km; 2 - q = 0.5 astronomical units; D_{O-} = 1 km; 3 - q = 4 astronomical units; D_{O-} = 0.25 km; 4 - q = 4 astronomical units; D_{O-} = 1 km.
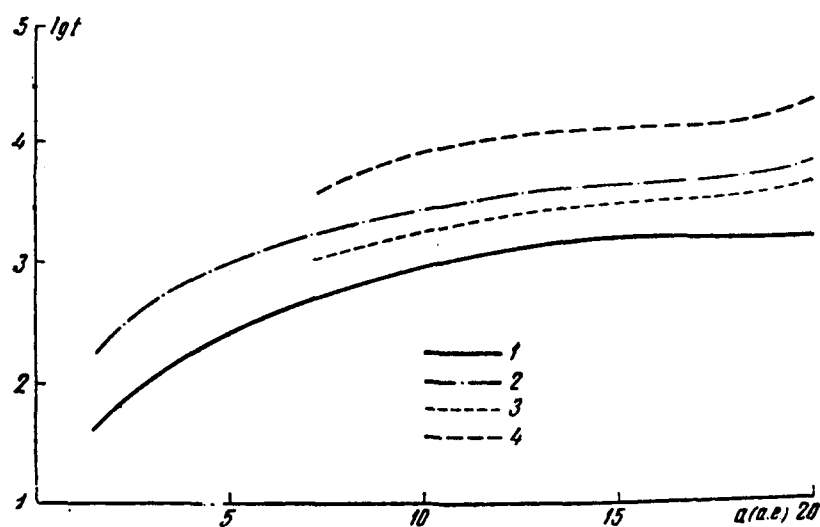
Figure 2.   Lifetime of cometary nucleus of C_2H_2 ice (t in years).
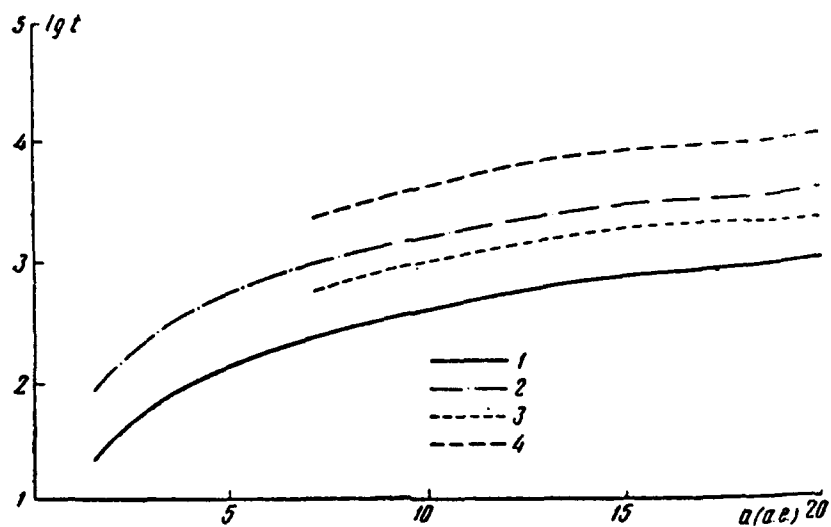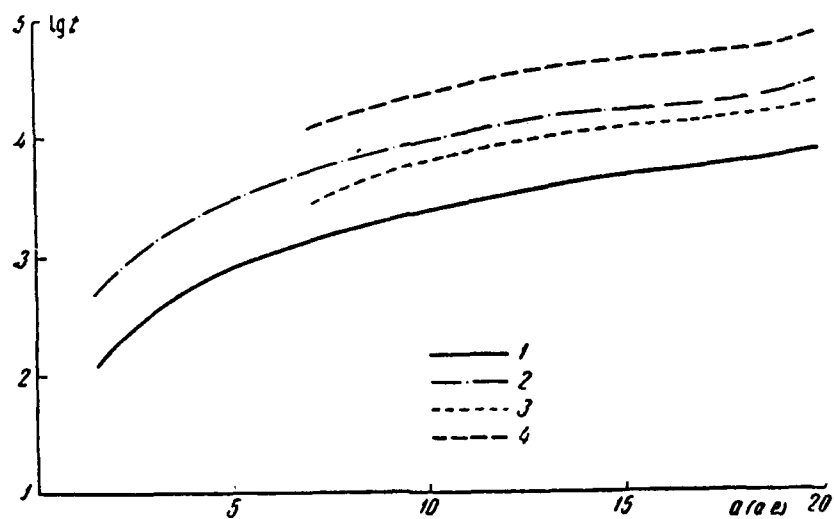Notation same as in Figure 1.

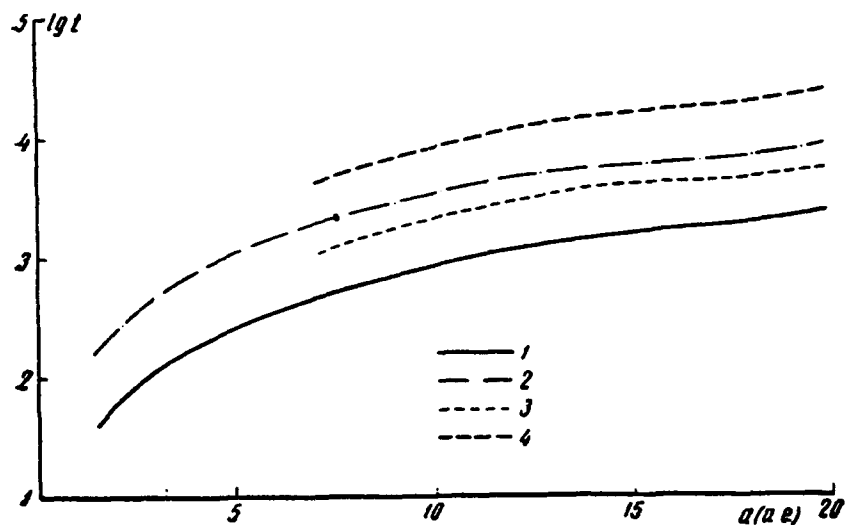Figure 3. Lifetime of cometary nucleus of NH_3 ice (t in years). Notation same as in Figure 1.

Figure 4. Lifetime of cometary nucleus of CH_4 ice (t in years). Notation same as in Figure 1.
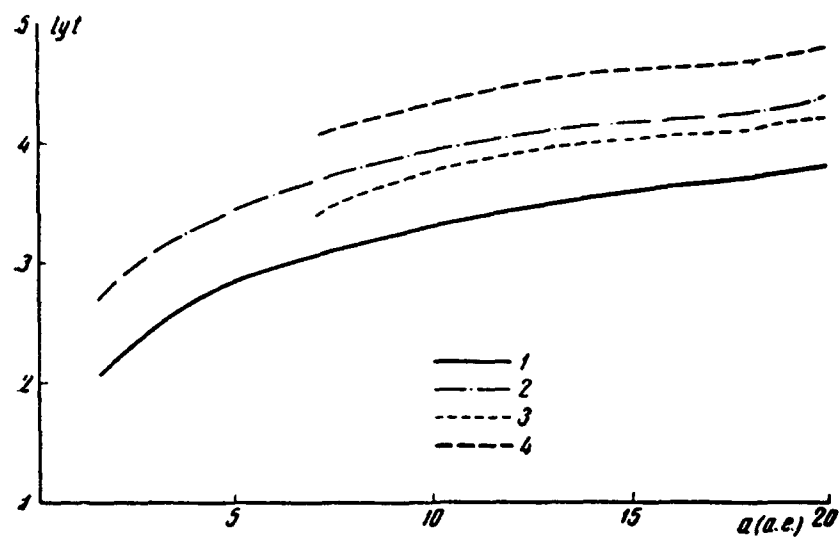
Figure 5. Lifetime of cometary nucleus of CO_2 ice (t in years).

Figure 6. Lifetime of cometary nucleus of C_2N_2 (t in years).

Notation same as in Figure 1.

Indeed, the intensity of corpuscular radiation from the Sun for r = 1 astronomical unit is equal to

$$E_{\text{к}}^0 = n_0 v_0 \frac{m_{H^+} v_0^2}{2} = n_0 \frac{m_{H^+} v_0^3}{2},$$ (8)

where n_0 is the concentration of protons, m_{H^+} is the mass of a proton. When $n_0 = 6 \cdot 10^2$ cm^{-3}, $v_0 = 5 \cdot 10^7$ cm/sec (Ref. 9), and $E_K^0 = 62$ ergs/cm^2-sec. At the same time, the intensity of the photon radiation from the Sun $E_{Ph} = 1.36 \cdot 10^6$ erg/cm^2-sec. Therefore the number of molecules evaporated from one square centimeter in one second $E_{Ph}^0/E_K^0 = 2.2 \cdot 10^4$ times the number of molecules evaporated by corpuscular radiation from the Sun.

However, the situation changes materially in favor of corpuscular radiation when one considers the conversion of the evaporated molecules in the field of radiation of the Sun. The transformation schemes for C_3H_6, C_2H_2, C_2N_2, NH_3, CO_2, H_2O, and CH_4 (Ref. 9) show that corpuscular radiation plays a larger role than photon radiation in the ionization and dissociation of cometary molecules.

Now, let us use the example of formation of H_2O molecules from OH and H to examine the role of processes of recombination of molecules in comets at the same distance as Jupiter from the Sun.

The most probable processes of destruction of H_2O molecules and their products of decomposition, as shown by the conversion scheme for water molecules in comets, are the following (Ref. 9): $H_2O + H^+ \rightarrow OH^* + H^+ + H - 9$ ev with an effective cross section $\sigma_{H_2O} = 2.03 \cdot 10^{-15}$ cm^2 and $OH + H^+ \rightarrow O^* + H^+ + H - 6.4$ ev. ($\sigma_{OH} = 2.71 \cdot 10^{-15}$ cm^2). The symbol * denotes an excited molecule. The reverse process will be the process $H + OH \rightarrow H_2O$.

Stable H_2O molecules are formed from OH molecules and H atoms only if the molecule which is formed is deprived in some way of part of the energy liberated in its formation.

The transmission of excess energy can be accomplished either by radiation of the energy or by transferring it to a third particle at the

time of collision of the atoms (triple collision).

First, let us consider the case of stabilization of H_2O molecules by radiation. Here two cases are possible.

1. Stabilization of an H_2O molecule by radiation of vibration quanta. This case holds only in the formation of a molecule from different radicals and atoms, which is true in our case. Let us find the effective cross section of the process $OH + H \rightarrow H_2O^*$ with radiation of vibration quanta ($H_2O^* \rightarrow H_2O + h\nu$). The effective cross section of such a process of stabilization of an H_2O molecule with radiation of vibration quanta is determined by the expression

$$\sigma_1 = \frac{\tau}{\tau_0} \cdot \sigma_0, \tag{9}$$

where $\sigma_0 = 5.3 \cdot 10^{-16}$ cm^2 is the gas kinetic cross section of a H_2O molecule, τ_0 is the average lifetime of an excited molecule, τ is the duration of collision of OH molecules and H atoms. The latter is equal to

$$\tau = \frac{2D_{OH}}{\overline{v}_{OH}}, \tag{10}$$

where $D_{OH} = 2.2 \cdot 10^{-8}$ cm, the diameter of an OH molecule.

If we set $\overline{v}_{OH} \approx \overline{v}_{H_2O}$, then $\overline{v}_{OH}$ is the arithmetical mean of the velocity of OH molecules determined by formulas (Ref. 5):

$$\overline{v}_{OH} = \sqrt{\frac{8kT}{\pi m}}, \tag{11}$$

$$T = \left[(2\pi m_{H_2O} k) \left(\frac{E_0}{r^2 a_2 L_{H_2O}} \right)^2 \right]^{\frac{1}{2\beta - 1}} \tag{12}$$

Substituting into this formula for molecules $H_2O = m_{H_2O} = 2.99 \cdot 10^{-23}$ grams, $L_{H_2O} = 11$ kcal/mole $= 1.83 \cdot 10^{-20}$ kcal, $a_2 = 5 \cdot 10^{-41}$ molecules/cm^2-sec, $\beta = 18.0$ (Ref. 5), we obtain $T = 154^\circ$ K for $r = 5.2$

astronomical units.

The quantity τ_o can be determined as the time of damping of a classical vibrator (Ref. 10):

$$\tau_0 = \frac{3}{8\pi^2}\frac{c\mu}{e^{*2}}\lambda^2,\tag{13}$$

where c is the speed of light (c = $3\cdot10^{10}$ cm/sec), μ is the derived mass of a H_2O molecule:

$$\mu = \frac{m_{H_2O}m_H}{m_{OH} + m_H} = 1{,}57\cdot10_r^{-24},\tag{14}$$

is the wavelength of vibration quanta of a water molecule

$$\lambda = 9440 \overset{o}{A} = 9.44\cdot10^{-5} \text{ cm;}\tag{15}$$

$e* = \dfrac{P}{r_o}$ the effective charge where P is the dipole moment of a H_2O molecule ($P_{H_2O} = 1.5\cdot10^{-18}$), r_o is the equilibrium distance between atoms in a H_2O molecule (r_o = $9.72\cdot10^{-9}$ cm).

The velocity of motion of a H_2O molecule corresponding to a temperature of T = 154° K will be equal to $\bar{v}_{H_2O}$ = $4.26\cdot10^4$ cm/sec.

The final formula for the effective cross section will have the form

$$\sigma_1 = \frac{16\pi^2 D_{OH}}{3c\mu\bar{v}_{OH}\lambda^2}\left(\frac{P}{r_0}\right)^2\sigma_0\tag{16}$$

and

$$\sigma_1 = 6{,}56\cdot10^{-25} \text{ c.}\mu^2.$$

The number of H_2O molecules formed in the process OH + H $\rightarrow H_2O*$ with radiation of vibration quanta is determined by the expression

$$z_1 = \sigma_1\bar{v}n_H n_{OH},\tag{17}$$

where $\bar{v}$ is the mean relative velocity of OH molecules and H atoms, n_H and n_{OH} are the concentrations of H atoms and OH molecules respectively formed in the decomposition of H_2O molecules at a distance of the radius of the sphere of existence of H_2O molecules--R_{H_2O}.

Let us calculate the values of the concentration of OH molecules and H atoms. For this we must first know the quantity $n_{H_2O}^0$--the concentration of H_2O molecules close to the cometary nucleus. It can be found from the formula

$$n_{H_2O}^0 = \frac{1}{kT} a_2 \left[(2\pi mk) \left(\frac{E_0}{a_2 r^2 L_{H_2O}} \right)^2 \right]^{\frac{\beta}{2\beta - 1}}$$

(18)

and is equal to

$$n_{H_2O}^0 = 4.71 \cdot 10^{12} \, cm^{-3}.$$

Now we shall calculate the values of n_{OH} and n_H.

The series of conversions of complex parent molecules when they are destroyed in the field of photon and corpuscular radiation from the Sun are similar to series of radioactive transmutations (Ref. 11). For small intervals of time in which the intensity of photon and corpuscular radiation from the Sun can be considered constant, the theory of radioactive transmutations can also be applied to processes of decomposition of H_2O molecules in comets (Ref. 11).

The largest quantity of OH molecules and H atoms are formed at the distance from the nucleus

$$R_{H_2O} = \bar{v}_{H_2O} \tau_{H_2O},$$

where τ_{H_2O} is the lifetime of H_2O molecules. At a distance R_{H_2O} the majority of H_2O molecules evaporated from the cometary nucleus turn out to be dissociated into OH and H. The value of the concentration of OH molecules and H atoms formed as a result of the process

$H_2O + H^+ \rightarrow OH^* + H^+ + H$ at the distance $R = R_{H_2O}$ from the cometary nucleus is determined, according to the theory of dissociative decomposition (Refs. 11, 12), for the chain $H_2O \rightarrow OH + H$ by the expression

$$n_{OH}(t = \tau_{H_2O}) = \frac{R_{o-}^2}{R_{H_2O}^2} n_{H_2O}^0 \frac{\tau_{OH}}{\tau_{H_2O} - \tau_{OH}} \left(e^{-\frac{\tau_{H_2O}}{\tau_{H_2O}}} - e^{-\frac{\tau_{H_2O}}{\tau_{OH}}} \right), \qquad (19)$$

where R_{o-} is the radius of the cometary nucleus. For a mass $M = 10^{10}$ grams for a spherical nucleus of H_2O ice $R_{o-} = 1.44 \cdot 10^3$ cm.

τ_{OH} and τ_{H_2O} are the lifetimes of OH molecules and H_2O molecules, where

$$\tau_{OH} = \frac{r^2}{\sigma_{OH} v_{H^+} n_{H^+}}, \qquad (20)$$

$$\tau_{H_2O} = \frac{r^2}{\sigma_{H_2O} v_{H^+} n_{H^+}}, \qquad (21)$$

where r is given in astronomical units and $v_{H^+} n_{H^+} = 3 \cdot 10^{10}$ cm^{-3}-sec^{-1} for $r = 1$ astronomical unit (Ref. 9).

For $r = 5.1$ astronomical units, $\tau_{H_2O} = 4.42 \cdot 10^5$ sec, $\tau_{OH} = 3.34 \cdot 10^5$ sec.

The radius of existence of a H_2O molecule

$$R_{H_2O} = 1.88 \cdot 10^{10} \text{ cm}. \qquad (22)$$

After substituting the values derived above into (19) we obtain $n_{OH} = n_H = 8.55 \cdot 10^{-3}$ cm^{-3} for $R = R_{OH}$. Then

$$Z_1 = \sigma_1 r n_H n_{OH} = 2,04 \cdot 10^{-24} \text{ см}^{-3} \text{сек}^{-1}, \qquad (23)$$

that is, the rate of formation of H_2O will be exceedingly small.

2. Stabilization of H_2O molecules can also be accomplished by radiation connected with electron transition.

The duration of collisions of OH molecules with H atoms is equal to

$$\tau = \frac{2D_{OH}}{\overline{v}_{OH}},$$ (24)

where

$$\overline{v}_{OH} \approx \overline{v}_{H_2O}.$$

The lifetime of an excited H_2O molecule for electron transition $\tau_o \approx 10^{-8}$ seconds. Therefore the effective cross section σ_2 for the process of formation of H_2O molecules from OH and H with radiation of the excess energy by electron transition is determined by the expression

$$\sigma_2 = \frac{2D_{OH}}{\overline{v}_{H_2O} \cdot \tau_0} \sigma_{OH}$$ (25)

and will be equal to $\sigma_2 = 3.02 \cdot 10^{-20}$ cm^2 with a gas kinetic cross section of an OH molecule $\sigma_{OH} = 3.19 \cdot 10^{-16}$ cm^2.

The rate of formation of stable H_2O molecules from OH and H when the H_2O molecules lose their excess energy through radiation connected with electron transition will be equal to

$$Z_2 = \sigma_2 \overline{v}_{H_2O} n_{OH} n_H = 9,4 \cdot 10^{-20} \; cm^{-3} sek^{-1},$$ (26)

that is, the process of formation of H_2O molecules from OH and H connected with radiation of excess energy by electron transition is 5 orders more effective than the formation of H_2O by the process connected with the radiation of vibration quanta.

Now, let us consider the process of formation of H_2O molecules as a result of triple collisions $(OH + H + H_2O \longrightarrow H_2O + H_2O)$. The H_2O molecule which has been formed at this time transfers its excess energy to another H_2O molecule and becomes more stable after this. In spite of the fact that the quantity of OH molecules and H atoms close to the cometary nucleus should be extremely small (the lifetime of a H_2O molecule for $r = 5.2$ astronomical units is long--on the order of 10^5 seconds), the greatest number of triple collisions will take place close to the cometary nucleus since $n_{H_2O}^o \gg n_{OH}$ and n_H for $R = R_{H_2O}$.

Let us find the values of n_{OH}^o and n_H^o, by making use of the theory of dissociative conversions for the chain $H_2O \longrightarrow OH \longrightarrow H \longrightarrow H^+$ for the time $t = 1$ second after the beginning of these conversions close to the nucleus.

We selected a fairly small time interval ($t = 1$ second) in view of the fact that H_2O molecules in a space of 1 cm^3 which are found close to the cometary nucleus at first, move away from the nucleus with a thermal velocity of several hundreds of meters per second, will turn out to be in an ever larger space with the passage of time; that is, they will be diluted by the inverse square law R^{-2}, which will have a very unfavorable effect on the number of triple collisions per unit volume for large values of t. Therefore, our selection of $t = 1$ second defines the most favorable case for triple collisions.

According to the theory of dissociative conversions (Refs. 11, 12), the values of n_{OH} and n_H will be found by the formulas:

$$\dot{n}_{OH}^0 = n_{H_2O}(0) \frac{\tau_{OH}}{\tau_{H_2O} - \tau_{OII}} \left(e^{-\frac{t}{\tau_{H_2O}}} - e^{-\frac{t}{\tau_{OH}}} \right), \qquad (27)$$

It will have the following form after replacing $\dfrac{\tau_{OH}}{\tau_{II_2O} - \tau_{OII}}$ by the quantity $\dfrac{HO_0 - O'H_0}{IIO_0}$ (since $\tau \sim \sigma$):

$$n_{\text{OH}}(t = 1 \ cek) = n^0_{\text{OH}} = n_{\text{H}_2\text{O}}(t = 0) \frac{\sigma_{\text{OH}}}{\sigma_{\text{H}_2\text{O}} - \sigma_{\text{OH}}} \left(e^{-\frac{1}{\tau_{\text{H}_2\text{O}}}} - e^{-\frac{1}{\tau_{\text{OH}}}} \right) \cdot (28)$$

Substituting in (28) the quantities $n_{\text{H}_2\text{O}}(0) = 4.71 \cdot 10^{12} \ cm^{-3}$,

$\sigma_{\text{H}_2\text{O}} = 2.03 \cdot 10^{-15} \ cm^2$, $\sigma_{\text{OH}} = 2.71 \cdot 10^{-15} \ cm^2$, $\tau_{\text{H}_2\text{O}} = 4.42 \cdot 10^5$ sec, $\tau_{\text{OH}} = 3.34 \cdot 10^5$ sec, $\sigma_{\text{H}} = 1.88 \cdot 10^{-15} \ cm^2$ (Ref. 9) for the process $\text{H} + \text{H}^+ \rightarrow \text{H}^+ + \text{H}$ we obtain $n^0_{\text{OH}} = 1.06 \cdot 10^7 \ cm^{-3}$.

The quantity n^0_{H} can be determined from the expression (Ref. 12):

$$n_{\text{H}}(t = 1 \ cek.) = n^0_{\text{H}} = n_{\text{H}_2\text{O}}(0)(c_1 e^{-\lambda_1 t} + c_2 e^{-\lambda_2 t} + c_3 e^{-\lambda_3 t}), \qquad (29)$$

where $\lambda_1 = \frac{r_1}{\tau_{\text{H}_2\text{O}}}$, $\lambda_2 = \frac{1}{\tau_{\text{OH}}}$, $\lambda_3 = \frac{1}{\tau_{\text{H}}}$.

$$c_1 = \frac{\lambda_1 \lambda_2}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)} = \frac{\sigma_{\text{H}_2\text{O}} \sigma_{\text{OH}}}{(\sigma_{\text{OH}} - \sigma_{\text{H}_2\text{O}})(\sigma_{\text{H}} - \sigma_{\text{H}_2\text{O}})} = -53,9, \qquad (30)$$
$$\lambda_1 = 2,26 \cdot 10^{-6} \ cek.^{-1},$$

$$c_2 = \frac{\lambda_1 \lambda_2}{(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)} = \frac{\sigma_{\text{H}_2\text{O}} \sigma_{\text{OH}}}{(\sigma_{\text{H}_2\text{O}} - \sigma_{\text{OH}})(\sigma_{\text{H}} - \sigma_{\text{OH}})} = 9,77, \qquad (31)$$
$$\lambda_2 = 2,99 \cdot 10^{-6}.cek.^{-1},$$

$$c_3 = \frac{\lambda_1 \lambda_2}{(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)} = \frac{\sigma_{\text{H}_2\text{O}} \sigma_{\text{OH}}}{(\sigma_{\text{H}_2\text{O}} - \sigma_{\text{H}})(\sigma_{\text{OH}} - \sigma_{\text{H}})} = 44,2, \qquad (32)$$
$$\lambda_3 = 2,1 \cdot 10^{-6} \ cek.^{-1}.$$

Substituting the values of λ_1, λ_2, λ_3, c_1, c_2, c_3 into (29) we obtain $n^0_{\text{H}} = 9.42 \cdot 10^6 \ cm^{-3}$.

Let us find the expression for the rate of formation of H_2O molecules in triple collisions. For the process $\text{OH} + \text{H} + \text{H}_2\text{O} \rightarrow \text{H}_2\text{O}^* + \text{H}_2\text{O}$ a triple collision goes through the following stages:

    1) formation of the atomic pair $\text{OH} + \text{H} \rightarrow \text{H}_2\text{O} \ *$,

    2) stabilization of the pair by subtracting the energy of the

third particle--the H_2O molecule for the lifetime of the pair (OH, H).

Let us denote the number of double collisions between OH and H during one second in 1 cm^3 by $Z_{OH,H}$. The rate of formation of the pair (OH, H) can be set equal to

$$\frac{dn_{OH,H}}{dt} = I_{OH,H},\tag{ }$$

where $n_{OH,H}$ is the concentration of pairs (OH, H). The equilibrium concentration of pairs (OH, H) will be equal to

$$n^0_{OH,H} = Z_{OH,H}\tau.\tag{34}$$

Then the number of triple collisions with formation of stable H_2O molecules from OH and H can be determined as the number of double collisions between these pairs (OH, H) on one hand and H_2O molecules on the other hand; they will be equal to (Ref. 10):

$$Z_3 = 2\sqrt{2\pi}\, D^{*2}_3 \left(\frac{RT}{\mu_1}\right)^{1/2} n^0_{OH,H}\, n^0_{H_2O},\tag{35}$$

where D^{*2}_3 is the effective diameter of the OH, H, and H_2O system for triple collision. It characterizes the probability of formation of H_2O molecules in triple collisions. Let us take the optimum case in which D^*_3 is equal to the sum of the gas kinetic diameters of the H_2O and OH molecules and the H atom

$$D^*_3 = D_{H_2O} + D_{OH} + D_H = 5.29\cdot10^{-8}\,cm,$$

μ_1 is the derived mass of the H_2O, OH, and H system

$$\mu_1 = \frac{1}{\frac{1}{m_{OH} + m_H} + \frac{1}{m_{H_2O}}} = 9\ g/mol.\tag{36}$$

The equilibrium number of OH, H pairs is equal to

$$n^0_{OII, II} = 2 \sqrt{2\pi} \left(\frac{RT}{\mu}\right)^{1/2} n_{OII}, \; n_H \frac{\Sigma g_i^* D_{2i}^{*}\tau_i}{\Sigma g_i}, \tag{37}$$

where D^*_{2i} is the effective diameter of the (OH, H) pair in the i-th electron state, τ_i is the lifetime of the pair in the i-th excited state, $\mu = \frac{\cdot m_{OH} m_H}{m_{OH} + m_H} = 0.944$ g/mole (mass μ is given in atomic units) is the derived mass of the pair, Σg_i^* is the sum of the statistical weights of stable electron states of the H_2O molecule arising out of normal states of the OH molecules and H atoms, Σg_i is the sum of all states in general of H_2O molecules arising out of the same molecular states.

Thus, the final expression of the number of triple collisions will have the following form:

$$Z_3 = 8\pi \frac{RT}{(\mu\mu_1)^{1/2}} \frac{\Sigma g_i^*}{\Sigma g_i} \overline{D_{2i}^{*}\tau_i} \overline{D_3^{*}} n_{OH} n_H n_{H_2O}. \tag{38}$$

For simplicity we shall set

$$\frac{\Sigma g_i^* D_{2i}^{*}\tau_i}{\Sigma g_i} = \overline{D_2^{*}\tau}, \tag{39}$$

where $D_2^{*2} = (D_{OH} + D_H)^2 = 9.1\cdot 10^{-16}$ cm^2 is the effective diameter of the pair (optimal), $\cdot\bar\tau$ is the average time that the H atom is close to the OH molecule at the time of double collision (Ref. 10).

One can set

$$\bar\tau = \frac{2\cdot (D_{OH} + D_H)}{\bar v_{H_2O}} = 1,42\cdot 10^{-12} \tag{40}$$

Then the expression for Z_3 acquires the simpler form:

$$Z_3 = 8\pi \frac{RT}{(\mu\mu_1)^{1/2}} \overline{D_2^{*}\tau} \overline{D_3^{*}} n^0_{OH} n^0_H n^0_{H_2O}; \tag{41}$$

$\overline{D_3^{*2}} \approx \overline{D_3^{*2}} = 2.8 \cdot 10^{-15}$ cm^2. Substituting into (41) the values of

$\overline{D_2^{*2}}$, $\overline{D_3^{*2}}$, $\bar{\tau}$, n_{OH}^o, n_H^o, $n_{H_2O}^o$, we obtain

$$Z_3 = 6.45 \cdot 10^{-5} \text{ cm}^{-3}\text{sec}^{-1}$$

the rate of formation of stable H_2O molecules as a result of triple

collisions.

Now, let us find the rate of destruction of H_2O molecules for the

process $H_2O + H^+ \longrightarrow OH* + H^+ + H$. The effective cross section for this

process $\sigma_4 = 2.03 \cdot 10^{-15}$ cm^2. The rate of dissociation of H_2O molecules

$$Z_4 = \sigma_4 \frac{n_H^0 + n_H^0 + n_{H_2O}^0}{r^2} = 1{,}06 \cdot 10^7 \text{ см}^{-3}\text{сек}^{-1}. \qquad (42)$$

Thus, we have the following table for the rates of the processes for
forming H_2O molecules and the rates of destruction of H_2O molecules:

$$Z_1 = 2.04 \cdot 10^{-24} \text{ cm}^{-3} \text{ sec}^{-1},$$

$$Z_2 = 9.4 \cdot 10^{-20} \text{ cm}^{-3} \text{ sec}^{-1},$$

$$Z_3 = 6.45 \cdot 10^{-5} \text{ cm}^{-3} \text{ sec}^{-1},$$

$$Z_4 = 1.06 \cdot 10^7 \text{ cm}^{-3} \text{ sec}^{-1}.$$

Consequently, the rate of destruction of H_2O molecules in comets

is many orders higher than the inverse process of recombination of de-
composition products in the parent molecules.

The same thing can also be shown for the other molecules in co-
mets: CO_2, C_2N_2, CH_4, C_3H_6, and NH_3.

Observatory Ye. A. Pnomarev for valuable assistance in this work.

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X. A LIST OF THE METEORITES BELONGING TO THE COLLECTION OF THE DEPARTMENT OF PETROGRAPHY AND MINERALS OF THE SOFIA UNIVERSITY, BULGARIA

by Professor Ivan Kostov

Russian Text Page 155.

A. Bulgarian Meteorites

1. Meteorite from the vicinity of Gunoshnik Village, Troyanskiy Rayon, weight 1.475 kg, date of fall 28 April 1904 at 18 hours, 20 minutes.
2. Meteorite from the vicinity of Debnevo Village, Troyanskiy Rayon, weight 253 grams, date of fall 28 April 1904, 18 hours, 20 minutes.
3. Tektite from the city of Silistra, weight 0.15 grams, date of fall 19 July 1917, 7 hours.

B. Foreign Meteorites

		Weight (grams)	Date of Fall
1.	Gjilatelke	81	3 Feb. 1882
2.	Ergheo, Somaliland	80	Jan. 1889
3.	Kendal County	8	1887
4.	Mocs	5	3 Nov. 1882
5.	Knyahinya	65	9 Jul. 1866
6.	Rittersgruen	8	1883
7.	New Concord	6	1 May 1860
8.	Sokobanya	4	3 Oct. 1877
9.	Mincy	44	1856
10.	Grand Rapids	14	1883
11.	Hex River Mountains	8	1882
12.	Nelson County	12	1860
13.	Staunton	14	1858
14.	Dhurmsala	12	14 Jul 1860
15.	Mauerkirchen	4	20 Nov 1768
16.	Hollands Store	12	1887
17.	Toluca, Mexico	226.5	1784
18.	Canyon Diablo	359.5	- -
19.	Sacramento Mts., New Mexico	72.3	- -

NASA TT F-100
National Aeronautics and Space Administration.
METEORITICS - No. 19. (Meteoritika.) Ye. S.
Burkser, et al. June 1964. i, 206p. OTS price,
$3.50. (NASA TECHNICAL TRANSLATION F-100.
Translation of publication from Izdatel' stvo Akademii
Nauk SSSR, Moscow, 1960 (USSR))

This is a collection of 10 articles covering primarily
problems on the chemistry, composition, and absolute
age of meteorites. Results of studies on tektites and
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